Journal of Cleaner Production 408 (2023) 137134

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

True cost accounting of organic and conventional food production

Amelie Michalke[a,*], Sandra Köhler[b], Lukas Messmann[b], Andrea Thorenz[b], Axel Tuma[b], Tobias Gaugler[c]

[a] Chair of Sustainability Science and Applied Geography, University of Greifswald, Friedrich-Ludwig-Jahn-Str. 16, 17489, Greifswald, Germany
[b] Resource Lab, Center for Climate Resilience, University of Augsburg, Universitaetsstr. 12, 86159, Augsburg, Germany
[c] Nuremberg Institute of Technology Georg Simon Ohm, Keßlerplatz 12, 90489 Nürnberg, Germany

ARTICLE INFO

Handling Editor: Yutao Wang

Keywords:
External costs
True cost accounting
Sustainable agriculture
Life cycle assessment
Organic farming
Price policy

ABSTRACT

Agriculture is one of the world's biggest polluters. Consumers are misled towards demand of unsustainable and inadequately priced food products by an insufficient internalization of externalities. Shifting demand towards more sustainable dietary choices can lead to a sustainable transition of agri-food networks. In this study, we evaluate environmental damage economically: we combine environmental assessment of different food products with the internalization of their monetary impacts. Life Cycle Assessments are modeled for conventional and organic foods and different production scenarios. The quantified environmental impacts are combined with True Cost Accounting to adjust food prices according to their environmental impacts. Using this framework for 22 German agricultural products, we find that on average, crop production generates externalities of about €0.79 per kg for conventional and about €0.42 for organic products. Conventional milk and eggs cause additional costs of about €1.29 per kg on average in organic systems and about €1.10 in organic ones. Conventional and organic meat generate externalities of €4.42 and €4.22 per kg, respectively, with beef generating the highest costs of all. The environmental favorability of organic products is confirmed, but the resulting organic market prices after internalization still exceed conventional prices. Externalities represent a negative impact on societal welfare, which should be addressed by policies supporting transparent pricing approaches.

1. Introduction

Food consumption and production is linked to a host of global crises. Agriculture is a major driver of global warming, accounting for about a quarter of global greenhouse gas emissions (IPCC, 2014a). It is also the largest consumer of freshwater, requiring 69% of global withdrawals (UN, 2018), and is recognized as the main driver of deforestation (FAO and UNEP, 2020). The planetary capacities of additional nitrogen emissions have been reported to be exceeded in 2009 already (Rockström et al., 2009), with agricultural fertilizer use being the contributor. These developments are continuously putting pressure on environmental and societal systems.

A transformation of current agricultural systems towards more sustainable production would help to address these issues. Sustainability is described as a tripartite endeavor and should consider the environment as well as society and the economy (Purvis et al., 2019). However, current market prices do not reflect the social and environmental damage caused by the food production. The sector externalizes this damage to, for example, other countries through land use for feed production or to society through emissions that threaten the global population and future generations. This externalization of costs does not follow the UN's polluter-pays principle (UN, 1992) and leads to market distortions: a significantly lower market price – without considering all the consequences of production – leads to in higher demand, as seen in environmentally harmful dietary patterns, especially in developed countries (Behrens et al., 2017; Semba et al., 2020). Externalities are defined as one fundamental type of market failure (Stiglitz, 2000), as they are ultimately borne by actors who are not involved in their creation (Unerman et al., 2018; Hopwood et al., 2010). Their monetization and internalization is therefore pivotal for establishing environmental regulations, for reducing financial risk from environmental impact, and for achieving optimal resource allocation (PRI & UNEP, 2011; Pizzol et al., 2015; Nguyen et al., 2016). In order to maximize total societal welfare, the consumption of food products with high externalities must be reduced, as high demand drives high production. Hence, uninternalized environmental externalities consequently increase the

* Corresponding author.
E-mail address: amelie.michalke@uni-greifswald.de (A. Michalke).

https://doi.org/10.1016/j.jclepro.2023.137134
Received 17 October 2022; Received in revised form 22 March 2023; Accepted 6 April 2023
Available online 17 April 2023

agricultural environmental impacts and perpetuate the cycle of environmental and societal damage. The internalization, however, of external costs would lead to a reduction in unsustainable demand (Hussen, 2004; Sturm and Vogt, 2018).

True Cost Accounting (TCA) is one such tool that aims to internalize external costs into the market price of products. It has recently gained interest as an approach for policy measures improving the sustainability of the agricultural sector (Baker et al., 2020, Gemmil-Herren et al., 2021). TCA reports positive or negative impacts of a produced commodity in monetary terms that are not included in the production costs (Baker et al., 2020). TCA is therefore the combination of an environmental (or social) assessment and a subsequent cost (or benefit) analysis. Another term for the same principles, Full Cost Accounting (FCA), is emerging in the environmental economics literature (Bebbington et al., 2001), and has been used for monetary environmental valuation across different industries (Epstein et al., 2011, D'Onza et al., 2016, Herbohn, 2005). According to the meta-study by Jasinski et al. (2015), one calculation approach is the monetary valuation of Life Cycle Assessment (LCA) results. LCA, one focus of this study, is a common method for assessing a wide range of environmental impacts. Agricultural LCA studies often only evaluate specific impact categories, such as greenhouse gas emissions (Aguilera et al., 2015; Flysjö et al., 2012; Venkat, 2012), or confine to individual products (Bos et al., 2014; Buratti et al., 2017; Einarsson et al., 2018). Different approaches to monetizing LCA results are also discussed, not necessarily limited to the food-context (Eldh and Johansson, 2006; Weidema, 2009; Nguyen et al., 2016; Arendt et al., 2020). With the therein found principles, some studies calculate externalities for specific food products (Zhen et al., 2021; Estrada-Gonzales et al., 2020). However, a TCA for a variety of products and production scenarios, as well as the full spectrum of environmental indicators, has not yet been conducted. Pieper et al. (2020), for example, propose a framework for calculating climate costs based on LCA for basic foodstuff. We build on this framework and aim to address the research gaps in conducting a full LCA of various food commodities and farming practices combined with a monetary evaluation to eventually develop and establish a comprehensive environmentally focused TCA of food.

Therefore, we combine a comprehensive impact assessment of different food products with best-practice monetarization approaches. In detail, we assess the environmental life cycle impacts of 22 food products, representing a large variety and the majority of agricultural production in Germany, at the level of 18 LCA impact categories of the ReCiPe 2016 method (Huijbregts et al., 2017) for organic and conventional farming systems. Subsequently, environmental impacts are monetized based on the Environmental Prices Handbook (de Bruyn et al., 2018) and the German Federal Environmental Agency (Umweltbundesamt, 2020) to depict the value of food with internalized environmental externalities. In doing so, we show true prices (as the sum of current producer prices and calculated externalities) and demonstrate how price levels shift with internalized external costs. This method ultimately addresses the advised polluter-pays principle and is an attempt to bridge the gap between conventional and organic product prices.

This work sets out to answer the following research questions.

❖ ***RQ1***: What are the environmental impacts of 22 agricultural products in Germany in different conventional and organic scenarios?
❖ ***RQ2***: What are the external costs associated with these food products? How do producer prices change after the internalization of external costs according to the polluter-pays principle?

2. Materials, methods, and calculations

Fig. 1 illustrates the methodology applied to address RQ1 and RQ2. This hybrid approach combines the environmental method of LCA with the economic method of TCA to quantify external costs. LCA is well established for examining and comparing environmental benefits or drawbacks of alternative products, including agricultural commodities (Poore and Nemecek, 2018). There are several impact assessment methods for LCA. Commonly used and therefore also applied in this

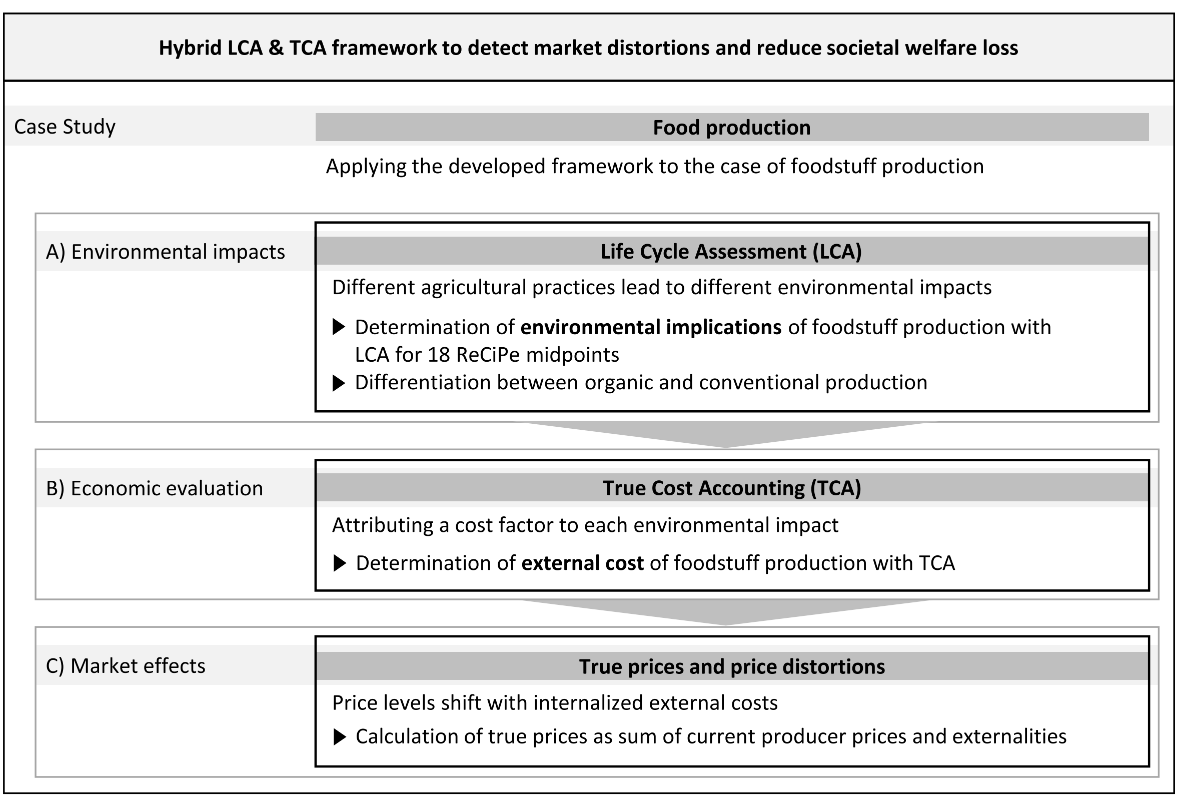

Fig. 1. Methodological framework of combined LCA (based on ISO 14040 and 14,044) & TCA.

study, is the ReCiPe method, which evaluates 18 different impact categories (midpoints) and associated environmental damages (endpoints) (Huijbregts et al., 2017). The herein proposed approach of the combination of LCA and TCA is applied to a case study on foodstuff in this work and builds on preliminary externality assessments (Pieper et al., 2020; Thi et al., 2016).

2.1. Goal and scope definition

The study's goal is comparative modeling and a monetized environmental impact assessment of 22 different products (for an extensive list, see Appendix A1), produced in Germany and assessed per 1 kg of product. First, a differentiation of production practices is modeled on Life Cycle Inventory (LCI) level. Second, the environmental impacts are monetized and hence represent the products' specific external costs. Finally, scenarios of production and monetization are used for sensitivity analysis (cf. section 3.3).

The system boundary for the comparative LCAs of organic and conventional food production is cradle-to-farmgate in Germany. LCIs from the Agri-Footprint (AFP) 5.0 database (van et al., 2019) are used for food production in the conventional base case. This database serves the purpose of our study and is used by previous LCA studies (e.g., van de Kamp et al., 2018; van Dooren and Aiking, 2016).

Product systems for plant- and animal-based products are included in Appendix A2. Agricultural production is often a multi-output system, e.g., in an arable crop system, grain production leads to the co-product straw. In these cases, environmental impacts are allocated according to the economic value of the co-products.

2.2. Life cycle inventories

To adjust conventional LCI data for organic production, we retrieve data on both production practices from two sources. First, the EU Council Regulation 834/2007 serves as the basis to define the means of production for organic processes. Second, a literature analysis is conducted to identify parameters concerning differences of the production practices. A detailed explanation of this analysis is provided in Appendices A3 and A7. We adjust the inventories of all processes within the system boundaries of the products (full inventories in Appendix A9, respective calculations in Appendix A3). Upstream processes and preproducts are modeled likewise. In the following details on the inventory adjustments are explained.

2.2.1. Yield

The yield describes the output per hectare for plant-based products and live weight per animal for animal products. Yield values differ between the data sources and within literature. Usually, organic yields are lower than conventional ones (de Ponti et al., 2012; Ponisio et al., 2015; Seufert et al., 2012) as nutritional inputs in organic agriculture are limited (see section 2.2.2). For milk and eggs, the yield defines the output of product per animal and year. Appendix A7(c) shows the average yield ratios between organic and conventional products, which we use for defining the organic base case. We find that the total average yield of organic plant-based production lies at 77.6% of conventional yield and is comparable to results of other studies (Seufert, 2018).

The total average yield of organic animals' live weight lies at 102.4%; however, organic animals' lifespan is 128.7% of conventional livestock, counteracting the supposed yield advantage. The output of milk and egg lies at 87.5% compared to the output of conventional dairy cows and laying hens. To account for the variability of yield values, we include this parameter in the sensitivity analysis (see section 2.4). All adaptions for organic produce are also incorporated in the upstream processes of livestock production, e.g., the yield for organic feed production is also adjusted.

2.2.2. Manure

There are several ways to model manure use (e.g., based on the plants' nutritional needs). AFP5.0 uses a country's livestock density to approximate the average amount of produced and applicable manure per hectare. We adopt this approach for modeling organic products for our base case scenario (see section 2.4) to remain consistent with the underlying database. This is a rather theoretical approach, which may not reflect reality fully, where manure application rates differ greatly between regions with high or low livestock density. However, we deem the approach suited to model German averages. This adaption of organic manure application results in pig manure use of 9.6% and poultry manure use of 54.4% of the amounts applied in conventional farming in the base case. However, in contrast, some literature suggests that organic farms may apply *additional* manure to achieve sufficient nutrient supply of soil and crops (de Backer et al., 2009; Nemecek et al., 2011). We identify seven case studies, where the manure application observed at organic farms (irrespective of the type of manure) is, on average, 56% higher than at conventional counterparts. This discrepancy in assumptions was accounted for in the sensitivity analysis (see section 2.4, Table 1). The manure values are provided in Appendix A8 (cells I494 to L496), where they are also used for subsequent calculations (e.g., heavy metal or N–P emissions).

Manure enters the farming system without any environmental burden from production, as it is entirely allocated to the respective manure producing animal husbandry. The impact caused by its application, however, is allocated to the respective manure-using crop cultivation. These crops are either for human or livestock consumption, and so the manure modeling is adapted for both plant- and animal-based products assessed in this study.

2.2.3. Energy consumption

Literature also suggests a difference between the energy input into organic or conventional systems. Diesel used for crop cultivation and transport, and energy used for heating and processing is adjusted according to the average difference from literature. Thereby, the calculation accounts for differences in livestock systems, since in organic livestock raising, outside housing is more common (Migliorini and Wezel, 2017). Due to limited data for specific food groups, we adjust electricity and diesel use for plant-based products (95.6% and 110.5%,

Table 1
Scenario definitions (base case and sensitivity analyses) of LCA & TCA. For the basis of evaluation, we combine the LCA results of two production base cases (O and C) with base case cost factors of the Environmental Prices Handbook. We model different production scenarios (O1–4) and combine all retrieved LCAs with different costing approaches to evaluate production practices and monetization sensitivities. Cost factors for all costing approaches are shown in Table S1-5.

	Life Cycle Assessment (LCA)		True Cost Accounting (TCA)	
Base Case	C	Conventional base case	E	Environ. Prices Handbook (EPH), average[a]
	O	Organic base case		
Sensitivity analyses	O1	yield (O) − standard deviation	E1	Environ. Prices Handbook (EPH), lower bound[b]
	O2	yield (O) + standard deviation	E2	Environ. Prices Handbook (EPH), upper bound[c]
	O3	manure (C)	E3	True Price Foundation (TPF)
	O4	manure (literature)		
Combination of all variations leads to **26** sensitivity analyses (in addition to the base cases)				

[a] For *global warming potential*, the price factor is derived from Umweltbundesamt (2020).
[b] For *global warming potential*, the price factor corresponds to the default value given by EPH.
[c] For *global warming potential*, the price factor is derived from Ricke et al. (2018).

respectively) and animal-based products (89.4% and 96.0%, respectively) based on the subordinate food categories (e.g., cereals for wheat, see Appendix A7(c)).

2.2.4. Feed intake

Outside housing also increases intake of grass and grass silage of beef cattle and decreases the need for compound feed. Therefore, a literature analysis on the feed intake of organic beef cattle resulted in an average of 84.7% compared to conventional beef cattle, which was used to adjust compound feed and, inversely, grass (silage) intake (see Appendix A7 (c)).

2.2.5. Lifespan

Lastly, the lifespan of livestock may differ between farming practices. Generally, also reflected in literature, organically raised livestock tends to live longer than conventional conspecifics (Alig et al., 2012; Boggia et al., 2010; Leinonen et al., 2012). This assumption may raise impacts per produced unit of meat and therefore is accounted for in organic farming with a parameter averaging values of livestock's increased lifespan from literature. This parameter is calculated for every animal-based product individually (see Appendix A7).

2.2.6. Pesticides and mineral fertilizers

Pesticides and mineral fertilizers in organic farming are limited and therefore removed from the LCIs for organic farming, as stated in the EU Council Regulation 834/2007. Affected are all listed pesticides and most listed fertilizers (except for lime fertilizer).

Moreover, emissions of nitrogen, carbon, phosphorus, and heavy metals are foremost impacted by fertilizers. Therefore, changes arising from remodeled organic inventories affecting air, groundwater, and soil emissions are calculated analogously to AFP 5.0. The latter is mostly based on the 2006 IPPC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and the EMEP/EEA air pollutant emission inventory guidebook 2016 (EMEP/EEA, 2016). Where applicable, we updated parameter values for the study at hand according to the 2019 refinement of these guidelines (IPCC, 2019) for both conventional and organic inventories. A detailed description of the inventory calculations is provided in Appendix A3, resulting parameter values are provided in, Appendix A8 and the application of the parameters in the LCIs is shown in Appendix A9.

2.2.7. Transport

Regulations of organic farming also restrict allowances of imported production means. Feed, for example, must be produced on-site or be imported from regional organic farms, or farms where standards are comparable. Among others, this adjustment mostly affects both transportation impacts and land transformation. For most crops considered in this assessment, land transformation values are either zero or rather small in AFP 5.0. However, especially compound feeds for conventional use include crops like soybeans from e.g., South America that are associated with higher values of land transformation. Transportation of feed has only few impacts on overall results (cf. Section 3.1). Due to the unspecific description of feed allowances for organic livestock in the EU regulation and following alleged variations in practices, assumptions for modeling an organic average process must be taken. Therefore, all feed, seeds, and other production originating outside of given local boundaries (Germany or Netherlands, if German processes are unavailable) are replaced in the inventories by the local equivalent with adapted weights and distances. This could potentially underestimate organic livestock impacts (cf. Section 3.4).

2.3. Life Cycle Impact Assessment and true cost accounting

To assess the impacts of all products and scenarios, we apply the LCA method ReCiPe 2016 (H) v1.1, with its 18 midpoints and three endpoints. Subsequently, the midpoint values are monetized and aggregated to the corresponding external costs of the foods, i.e., the total costs the product causes due to its inherent environmental damage as assessed with LCA. Furthermore, the gap between current market prices and costs due to uninternalized externalities is made apparent. Different approaches exist to monetarily estimate life cycle impacts with different underlying methods and values (Arendt et al., 2020). The monetizing method established in the Environmental Prices Handbook (EPH) utilizes monetizing factors that are largely congruent with ReCiPe 2008 (Goedkoop et al., 2009) impact categories (de Bruyn et al., 2018). Therefore, we additionally assess impacts with ReCiPe 2008 and combine the results with the cost factors of the EPH, since EPH's would thus be inconsistent with 2016 and distort the results, especially in the case of ecotoxicity. Costs are mainly expressed as damage costs (de Bruyn et al., 2018). Since costs for *global warming potential* are discussed in recent literature in more nuance and the costing factor given in EPH presents low in comparison, we decided to use damage costs derived from the Federal Environmental Agency of Germany (Umweltbundesamt, 2020), which also compare with the IPCCs evaluation of climate costs (IPCC, 2014). Cost factors used for the monetary evaluation of all midpoint categories are found in Appendix A5. In the sensitivity analysis (cf. section 2.4), four different sets of monetization are applied.

In order to assess the relative importance of the 18 midpoints, we calculate the contribution of each midpoint to its respective endpoint for each product and each scenario. In section 3, we focus on those midpoints that contribute at least 2% for the endpoints *human health* and *ecosystem quality* for at least one product in one scenario, which are *global warming potential*, *fine particulate matter formation*, *human non-carcinogenic toxicity*, *terrestrial acidification*, and *land use*. The midpoint-to-endpoint contribution is displayed in Figs. S1–4 (Supporting Information S1) and the full assessment is provided in Appendix A11 (columns BE to BZ, Supporting Information S2). In addition, we also show results for the midpoints *marine eutrophication* and *terrestrial ecotoxicity*, as they meet the same relevance criterion in terms of external costs after the monetization step.

2.4. Sensitivity analyses

In this section, uncertainties arising from the presented approach by connecting several methods, and using a multitude of data sources, are addressed. Table 1 shows the conventional and organic base case for the LCA and TCA approach, as well as the sensitivity analyses. The conventional base case (C) is defined by the default modeling in AFP 5.0 for each product. The organic base case (O) is adapted as explained in detail in section 2.2. The two base cases aim at describing the general average of German products. However, agricultural systems are complex, and practices vary from farm to farm, which has direct effects on the impacts arising for the products from these farms. Therefore, we model several variations of agricultural practices within the sensitivity analysis to depict the range of possible results. Due to data limitations and varying literature values, the modeling of O underlies uncertainties, which mainly concern the yield and manure applied. To express such uncertainties by certain assumptions, we model four organic scenarios.

Ranges of yield per hectare found in literature are very high, since yield is influenced by many factors (prevailing weather, soil composition, crop rotations, etc.). We therefore model yield variances per product category with alternating standard deviations found in literature for all analyzed products in O1 and O2 (see Appendix A7(c)). This is done to describe cases of organic production that are more, or less yield efficient than the overall average. In scenarios O3 and O4, the impact of manure is analyzed to account for manure distribution that might differ from the area based approach used in AFP 5.0. Depending on, e.g., manure supply in the region or the produced plants nutrient demand, manure use also differs greatly among farms even within the same production practice. O3 assumes the organic base case yield, but conventional manure application rates to offset an alleged underestimation of impacts in organic production. O4 is also modeled with the organic base yield but includes an average literature-based manure application rate of 156.7% compared to conventional production. Both scenarios O3 and O4 represent the case that manure is exchangeable between organic and conventional farms (as is allowed under certain restrictions, cf. Section 2.2.1). Both scenarios are applied to plant- and animal-based products, since manure is also used for the production of feed, which is used within animal-based production.

Not only does the LCA modeling underlie uncertainties, but also the TCA approach. Depending on the pricing methods, results can change drastically. The base case E mostly conveys average prices from EPH. We use the lower bound (E1) and upper bound (E2) prices given in EPH for the sensitivity analyses. As described, the costing factor of *global warming potential* is discussed in more nuance. In order to not only rely on one source for this sensitive midpoint, we apply three costing approaches to sensibly depict the manifold possible evaluations of climate costs: for the base case (E), we use damage costs derived from the Federal Environmental Agency of Germany (Umweltbundesamt, 2020); for the lower bound (E1), we use the original cost factor of EPH, which draws on abatement costing (de Bruyn et al., 2018); the upper bound (E2) is depicted by the median social cost of carbon determined by Ricke et al. (2018). These three perspectives allow a critical and nuanced description of economic implications from impacts through this important midpoint. Additionally, we include the pricing set published by the True Price Foundation (E3) (Galgani et al., 2020).

3. Results

Subsection 3.1 discusses the environmental impacts within the two base cases and the influence of yield and manure parameters (sensitivity analyses O1–O4). Furthermore, overall process contributions on the exemplary categories of wheat and beef cattle are presented. In section 3.2, we present the true costs of all products within the two base cases. In addition, externalities are presented with their effects on the products' current market prices. Lastly, in 3.3, we analyze the total sensitivity of the combined LCA and TCA approaches. All results can be found in Appendix A11).

3.1. LCA results of yield and manure scenarios

Since yield and manure application significantly impact Life Cycle Impact Assessment (LCIA) an analysis of different scenarios is presented in the following. Fig. 2 shows the environmental impact of selected organic plant-based products in the base case scenario (green bars) relative to their respective conventional counterparts (100%, blue line) and how these results vary for scenarios O1–O4. This comparative assessment enables a direct comparison between the scenarios. Still, a comparison across product categories is not trivial, as the impacts of the conventional products vary for every product in absolute values.

The ranges of results vary between the products due to the varying yield gaps found in literature (depicted by O, O1, and O2). For some (e.g., lupins or potatoes), the subsequent relative variations in O1 and O2 compared to O are larger than for others (e.g., oat). The midpoint showing no benefits for any organic product and production scenario is *land use*. This result is reasonable since yields of organic products are consistently lower than conventional (cf. Appendix A7(c)) and *land use* only measures the used land area quantitatively. Disadvantages from yield differences do not influence the remaining midpoint categories significantly. Only scenario O1 with the lowest yield for organic production lies above conventional impacts from *global warming* for lupins.

The second decisive parameter, manure application, influences the results in many cases, depending on the importance of manure on the overall impacts, even more strongly than the yield. Scenarios O3 and O4 assume higher application rates compared to the base case (O). Especially for *human non-carcinogenic toxicity*, this leads to high impacts compared to C. Heavy metal emissions foremost impact this midpoint, either emitted to soil or water or taken in by the cultivated crops. This is also why negative impacts for organic wheat and rapeseed are notable particularly for this midpoint. When the heavy metal content in the

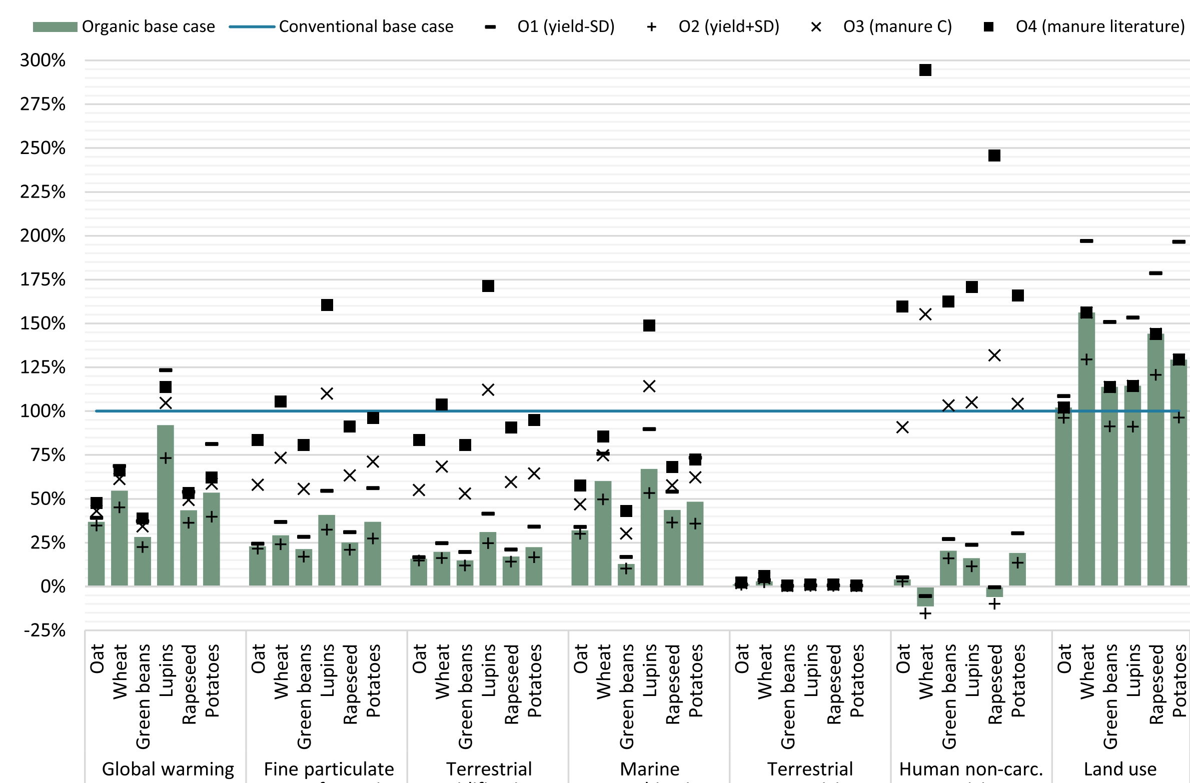

Fig. 2. Life Cycle Impact Assessment of organic (O) scenarios focusing on the impact of yield and manure differences compared to the conventional base case (C) as assessed with ReCiPe 2016.

harvested crops is higher than heavy metals emitted through fertilizer and manure application, this midpoint can present itself as negative. This fact can be misguiding, however, because those heavy metals emissions do not disappear with harvesting. The burden is merely shifted beyond the system's boundaries – they can distribute elsewhere, for example, during consumption or waste management of food.

While most organic products still perform better even with the same (O3) or higher (O4) manure input than conventional ones, this is different for lupins. The result of lupins is highly volatile towards manure use. As can be seen in scenarios O3 and O4 organic lupins result in higher (or identical) impacts than conventional ones throughout all presented midpoints. The counterpart to Fig. 2 for animal-based products is found in the Appendix A4 in Figure S1-5. For reasons of simplification, figures only include a selection of representative products for each food group and the seven most relevant midpoints for comparison. Please find the complete analysis and a more detailed look at the midpoints' relevance in Appendix A4, which also provides an analysis for all plant-based and animal-based products on midpoint and endpoint levels over all scenarios in absolute values.

3.2. Process contributions to LCA results

Furthermore, we show the composition of the midpoint values in more detail by analyzing each process's contributions within the system boundaries. We do this for wheat and beef cattle as representative examples of plant- and animal-based foods, to identify production steps with potential to reduce environmental impacts.

Decisive process contributions are quite heterogeneous across the midpoints in wheat, representing the category of cereals (cf. Fig. 3). While fertilizer for conventional wheat impacts *global warming*, *fine particulate matter formation*, *terrestrial acidification*, and *marine eutrophication* distinctively, it has little to no impact on *terrestrial ecotoxicity*. Impacts from fertilizers of organic products stem solely from lime; the associated impact is correspondingly small or even negative for human non-carcinogenic toxicity in the organic base case. This phenomenon is again explained due to plant uptake. Impacts on terrestrial ecotoxicity are primarily driven by plant protection like herbicides, pesticides, or fungicides. As neither are allowed in organic practices, the impact is close to zero for all organic products (cf. Appendix A4). Another pronounced contribution to *global warming* and *marine eutrophication* are impacts from foremost the emissions from crop residues, and the production of seeds and capital goods, all of which are combined in the group "Other". As we did not adapt crop residue emissions and capital goods for organic processes, higher impacts for organic agriculture per functional unit are due to yield differences.

These process contributions can differ for other plant-based products (see Appendix A4). For example, for legumes, the share of impacts from fertilizers is not as pronounced as for cereals. Here, instead of fertilizer, manure is the main contributor to *fine particulate matter formation* and *terrestrial acidification*, caused by its ammonia and nitrous oxide emissions, respectively. Crop residues also cause high nitrate emissions, which lead to increased impacts on *marine eutrophication*.

Process contributions for animal-based production are distributed somewhat differently. The reason for this is the upstream plant production before the actual life stage of the animal (cf. System boundaries, Appendix A2). For beef cattle (Fig. 4), for example, a very high contribution to overall effects is caused by grass or grass silage. Only for *terrestrial ecotoxicity* does the compound feed exceed grass impacts. The majority of this impact is caused by herbicides, pesticides, or fungicides used in conventional feed production. The animals' life stage does not contribute to all midpoints but strongly impacts *global warming*. Livestock emits GHG during digestion in ruminants and through their excrements. However, this result is bound to be reduced when including soil carbon sequestration (which is not considered in the LCIAs of AFP 5.0 and hence not in this study) and could potentially improve organic performance compared to conventional ruminants (Knudsen et al., 2019). Compared to plant-based products, organic production is not as beneficial, except for *terrestrial ecotoxicity*. Yield differences in the land use of feed and in live weight or feed intake per unit of animal disadvantage the environmental performance of organically raised livestock for most midpoints. For both food categories it is noticeable that transport and energy contributes rather small impacts along the process chain. This is in line with previous findings (Poore and Nemecek, 2018).

3.3. TCA results

In the following, results from LCA on midpoint level are put into perspective with their resulting costs induced to the environment and society. This procedure enables a depiction of the monetarily unaccounted damage from the production of foods.

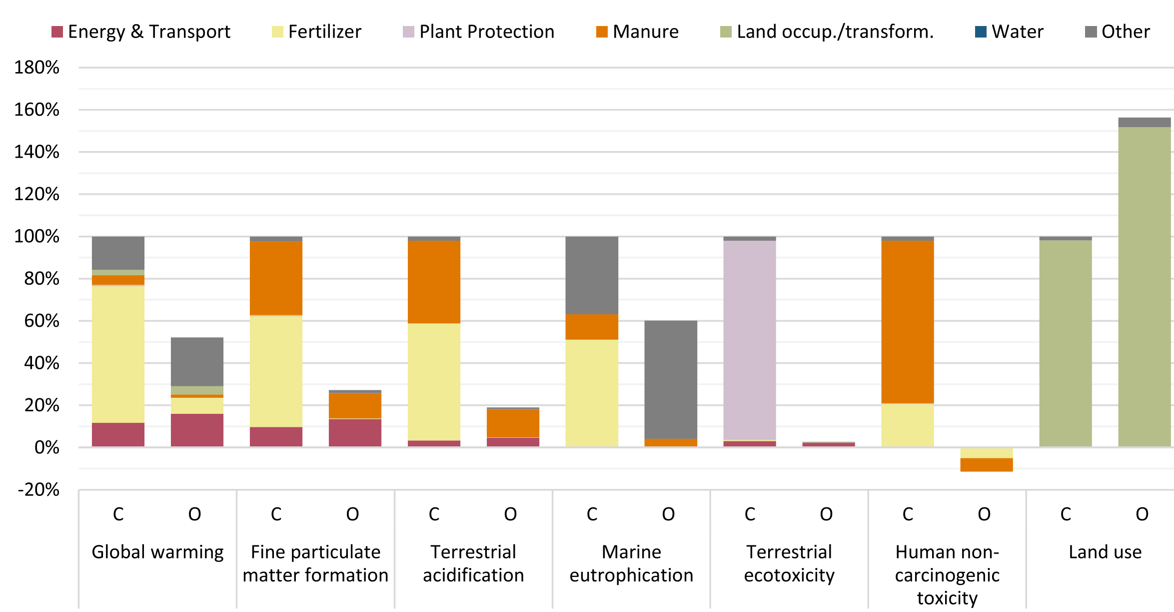

Fig. 3. Process contributions for conventional (C) and organic (O) wheat production as assessed with ReCiPe 2016. Processes included in "Energy & Transport" are inputs of diesel fuel on farm site (including associated transports of said fuel), and electricity used in stables. The category "Other" comprises crop residue emissions, and the production of seeds and capital goods. Process contributions for other products (maize, lupins, and rapeseed) are found in Appendix A4.

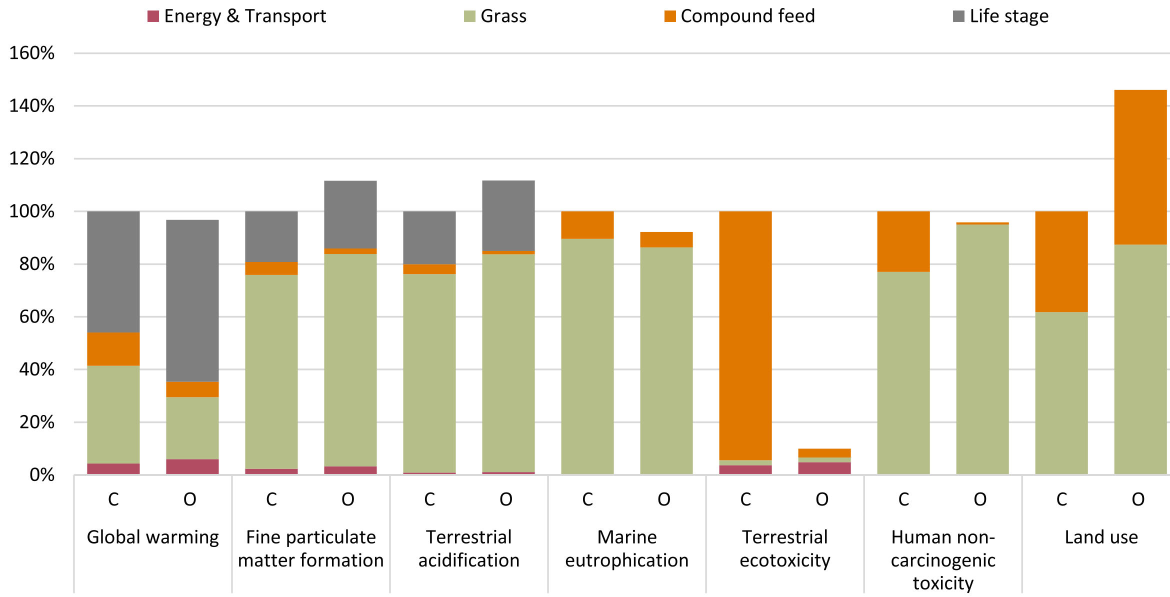

Fig. 4. Process contribution for conventional (C) and organic (O) beef cattle production as assessed with ReCiPe 2016. Process contributions for other products (milk, broilers, and eggs) are found in Appendix A4. Processes included in the contribution of "Grass" are application of fertilizers and manure with related emissions (namely N2O, NH3, CO2, NO3, P, and heavy metals), fuel consumption for agricultural machinery and its related emissions, and water for irrigation on the grassland. Processes included in "Energy & Transport" are inputs of diesel fuel on farm site (including associated transports of said fuel), the transport of feed from compound plant to the farm, and electricity used in stables. Processes included in "Compound feed" are the production of all feed components (i.a. barley, wheat, soybeans, etc.), as well as electricity used for the processing to compound. Finally, processes included in "Life stage" are enteric fermentation, and the manure management in stables including related emissions thereof (namely N2O and NH3).

In Fig. 5, producer prices of all plant-based foods (cf. Appendix A10) with their additional externalities based on the TCA with base case cost factors (E) are displayed. For reference, we also included upper and lower bounds of E1/E2 and an evaluation based on the True Price Foundation (Galgani et al., 2020; E3). Figures with an externality assessment for manure scenarios O3 and O4 can be found in Appendix A5, Figures S1-14 and S1-15.

Before externality valuation, the prices of organic products are

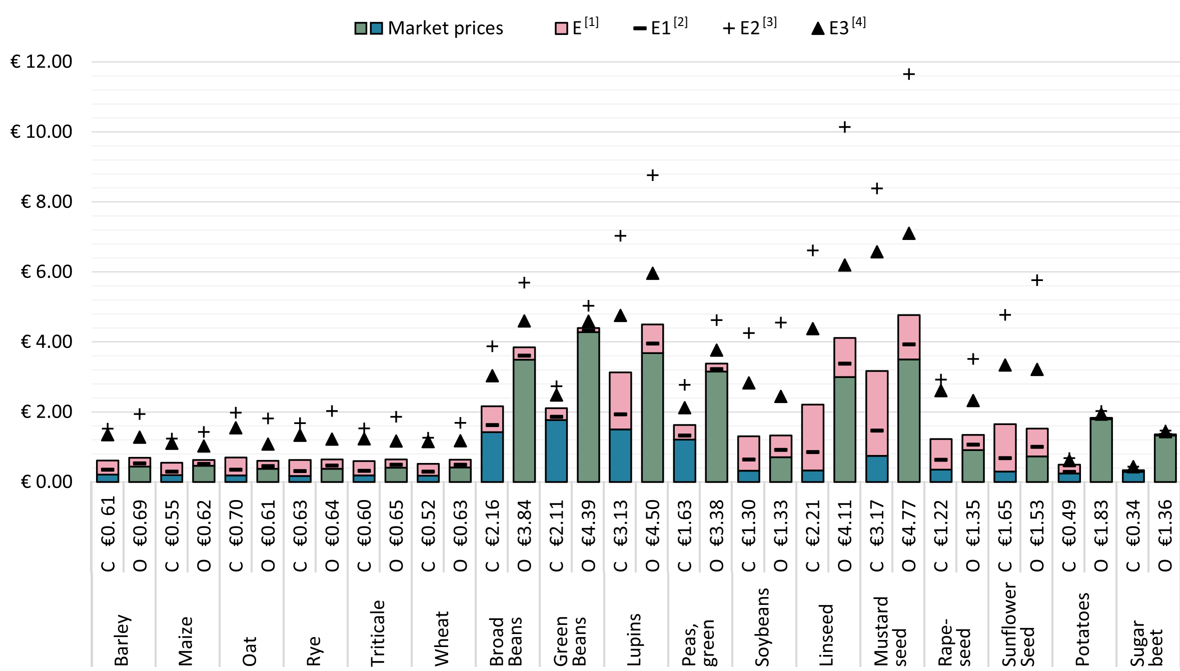

Fig. 5. Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) plant-based products in the base case. The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (see [1]). All results shown per kg of product and for the year of 2020. [1] E: For *global warming*, the price factor (0.20€/kg CO_2 eq.) is derived from Umweltbundesamt (2020); for all other midpoints, the average values from the Environmental Prices Handbook (EPH) are taken (de Bruyn et al., 2018); [2] E1: For *global warming*, the price factor (0.06€/kg CO_2 eq.) corresponds to the average value from the EPH; for all other midpoints, the lower bound values from the EPH are taken (de Bruyn et al., 2018); [3] E2: For *global warming*, the price factor (0.37€/kg CO_2 eq.) is derived from Ricke et al. (2018); for all other midpoints, the upper bound values from the EPH are taken (de Bruyn et al., 2018); [4] E3: All price factors are derived from the True Pricing foundation (Galgani et al., 2020).

consistently higher than of conventional products. This effect can be due to higher production costs for organic farmers (e.g., more labor input and lower yields), limited organic food supply, and more expensive marketing of smaller volumes. Generally, this gap cannot be bridged with internalizing LCA-based externalities alone. In the category of cereals, a general alignment of organic and conventional price levels is noticeable within the base cases. For legumes, the current market prices without externalities differ strongly between conventional and organic produce, with up to €2.51 per kg (for green beans). While externalities are consistently higher for conventional legumes and the price difference shrinks with internalization – in the case of soybeans only 3 cents more per organic kg – organic products remain the more expensive option also after internalization. This is the same for oilseeds, except for sunflower seeds, which after including externalities show a 12-cent price difference per kg in favor of organic produce. Also, for oats, a reversal of the current market situation is notable: after internalization, organic oat would be less expensive than conventional oat. The biggest current market price difference overall is seen in roots: conventional prices are only about 13% and 22% that of organic prices for potatoes and sugar beets, respectively. Internalized external costs are far from reversing this trend.

When combining LCA with the monetization method E3, the price levels of all cereals but wheat would change in favor of organic production; this also holds true for soybeans, rapeseed, and sunflower seed. E2 generally increases the difference between true prices of organic and conventional production. It also results in the highest costs of all monetization combinations for most foods. The influence of the underlying monetization method is further discussed in section 3.3.

In Fig. 6, animal-based products are displayed. Differences in externalities between the production practices are also far less pronounced. The highest externalities relative to the market price are caused by beef cattle (about 265% and 216% of the conventional and organic market prices, respectively). With €9.60 per kg, conventional meat from beef cattle would be over three times the price that is currently present on the market. However, the German beef production is not only based on beef cattle but also (among others) dairy cattle. Since it is a byproduct of the dairy industry, their environmental impact is allocated between milk and meat. Therefore, impacts and external costs are lower than for beef cattle, where 100% is allocated to meat. We account for these differences and the German cattle mix in Appendix A5, Figure S1-16.

After internalization, organic products are still more expensive than conventional ones for all animal-based products, but price gaps are reduced. Before internalization, organic market prices are on average 70% higher than conventional ones among all animal-based products. After internalization, this gap is 32%.

Regardless of the production scenario, it is observable that animal-based products generally entail higher external costs than plant-based products. In Tables S1–6, all external costs are presented in absolute figures, and relative to the market price of the products. In absolute terms, there are only some plant-based outliers (e.g., mustard- or linseeds) that have similar external costs to animal-based products. In relative terms, however, due to the low producer prices of plant-based food, the share in externalities is comparable between plant- and animal-based foods.

3.4. Sensitivity analysis

In sections 3.1 and 3.2, we discussed the sensitivity of LCA parameters and cost factors separately. However, the calculated external costs underlie uncertainties of both approaches, LCA and TCA. Therefore, Fig. 7 shows the range of results for externalities of plant-based products for all possible combinations of scenarios and pricing methods (cf. Table 1).

Results are somewhat volatile considering the underlying pricing scenarios. When considering conventional practices, externalities of rape seed, for example, range from €0.28 (E1) to €2.57 (E2) per kg. The highest range for organic practice overall is found in beef cattle, with

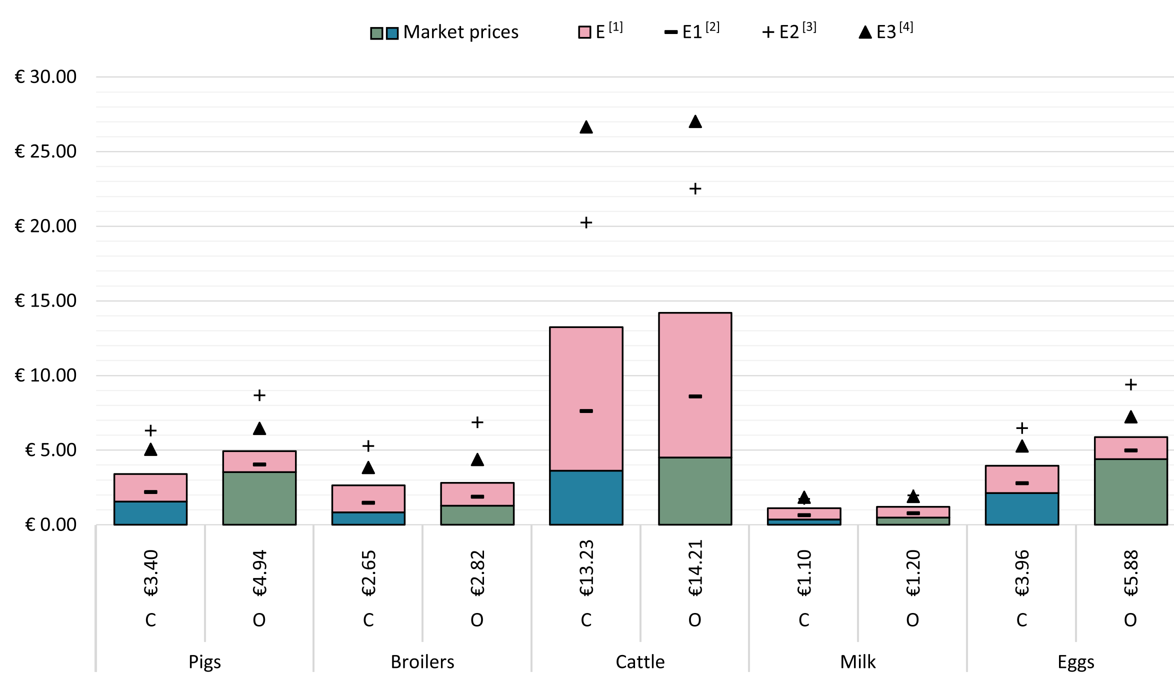

Fig. 6. Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) animal-based products in the base case. The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (see [1]). All results shown per kg of product and for the year of 2020. [1] E: For *global warming*, the price factor (0.20 €/kg CO_2 eq.) is derived from Umweltbundesamt (2020); for all other midpoints, the average values from the Environmental Prices Handbook (EPH) are taken (de Bruyn et al., 2018); [2] E1: For *global warming*, the price factor (0.06 €/kg CO_2 eq.) corresponds to the average value from the EPH; for all other midpoints, the lower bound values from the EPH are taken (de Bruyn et al., 2018); [3] E2: For *global warming*, the price factor (0.37 €/kg CO_2 eq.) is derived from Ricke et al. (2018); for all other midpoints, the upper bound values from the EPH are taken (de Bruyn et al., 2018); [4] E3: All price factors are derived from the True Pricing foundation (Galgani et al., 2020).

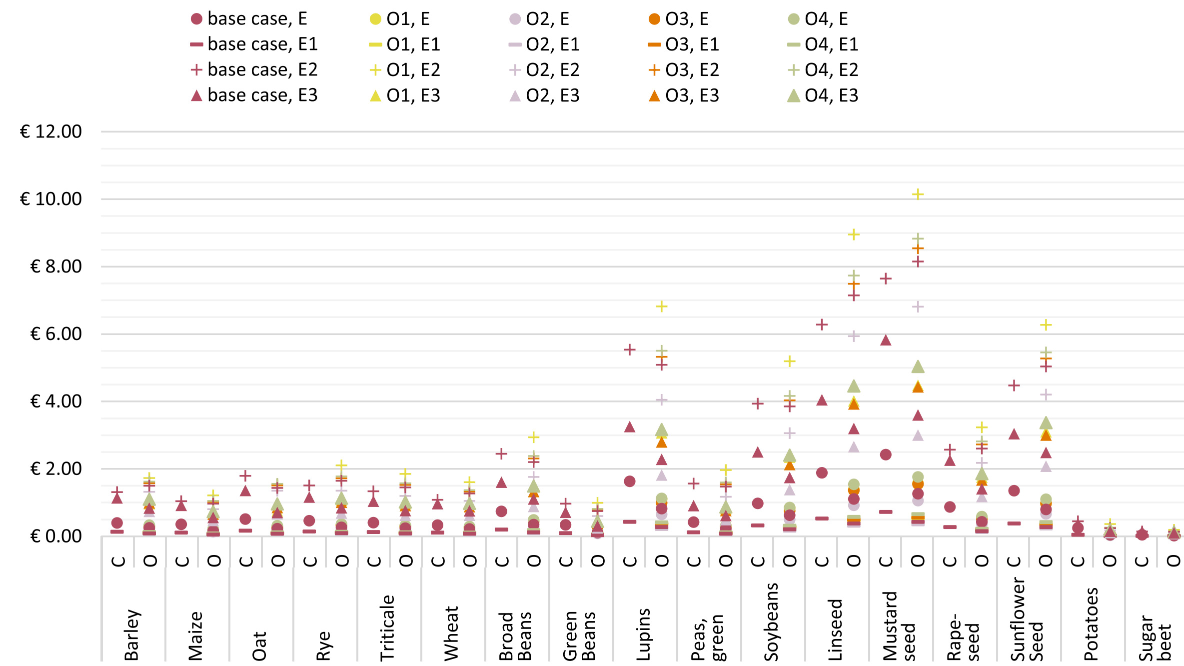

Fig. 7. All results shown per kg of product and for the year of 2020. Sensitivity analysis of externalities for conventional (C) or organic (O) plant-based products. The results are differentiated by all possible combinations of the organic base case (O) and scenarios O1–O4 with all pricing methods E, E1–E3 and the conventional base case with all pricing methods E, E1–E3. For a graphical animal-based sensitivity analysis, please see Appendix A5, for explanation of abbreviations to pricing methods and production scenarios, see Table 1 or Figs. 5 and 6. Animal-based counterpart can be found in Appendix A6, Figure S-17.

externalities reaching from €4.05–4.94 (with E1) to €22.46–27.78 (with E3) per kg. These large ranges underline the substantial uncertainties and variabilities when monetizing externalities of agricultural goods – and the pricing methods themselves.

Within a food category, the different farming scenarios do not result in as great of a price difference compared to the monetization methods. However, especially E2 generates high price varieties among different farming scenarios. This shows that even while using the same pricing method, it can make a significant difference under which conditions and requirements food is being produced.

Overall, monetization method E2, as the upper bound of EPH, delivers the highest externalities, except for beef. Lowest prices result from E1 as the lower bound of EPH in all cases. O1 mostly results in the highest externalities with any pricing scenario, indicating strong influences of lower yields on overall results. Exceptions are beef, broilers, and oat, where O4 induces the highest externalities, indicating a strong influence from manure on overall results. Also, within E1 impacts from manure contribute more relatively speaking than in other pricing scenarios, as highest externalities are mostly calculated for O4 (high manure rates from literature) over all organic scenarios.

4. Discussion

In this section, we draw conclusions from our results in terms of a sustainable transformation of food consumption (section 4.1), touch on subsequent policy and practical implications (section 4.2), discuss assumptions and limitations of the methods used (section 4.3), and provide an agenda for future research (section 4.4).

4.1. Paths for sustainable transformation

Environmentally speaking, the results underline the favorability for organic practices in most cases (see Fig. 2). However, based on the calculated true prices, consumers would, in many cases, choose conventional food. This is mainly due to the fact that organic market prices are higher than conventional ones, and the alleged environmental favorability compensates for this in only a few cases. A recent analysis of externalities, which considers greenhouse gas emissions and land-use change, finds very similar notions for conventional and organic foods (Pieper et al., 2020). However, increasing demand of organic products will likely decrease their market prices in the future, further closing the price gap towards conventional foods.

Regardless of the farming or pricing scenarios used for assessment, plant-based products largely entail lower externalities than animal-based products. These results follow previous findings on the environmental performance and the externalities of food products (Pieper et al., 2020; Poore and Nemecek, 2018). This notion is understandable, as process chains of livestock are complex and require more resources and generate consequently more emissions than plant production. Therefore, consumers' dietary behavior should evolve towards a more plant-focused diet, which would be supported by the rather drastic price increases of animal-based foods. This dietary transformation would contribute to reaching international sustainability goals and health benefits for consumers (Nelson et al., 2016; Willett et al., 2019).

4.2. Policy and practical implications

The large ranges of externalities, as described in section 3.3, have two implications: First, for an adequate assessment of the environmental impacts of food, it is vital to distinguish which production practices and conditions underlie the assessed system; second, monetization methods on midpoint level are subject to significant variations and should be further investigated. For beef cattle, for example, switching the pricing method can change the external costs by up to 5€ per kg. Generally, the higher the prices in certain scenario combinations, the less feasible they seem in practice (Michalke et al., 2022). While the results of section 3.3 show a wide range in results, products that make up the majority of German production (e.g., cereals, maize, sugar beet; Thorenz et al., 2018) are more stable across all scenarios. In any case, we argue that this approach indicates the high and manifold externalities borne by societal demand for food that need to be addressed in economic policy. Currently, natural resources are used for production without compensating for the resulting ecological pressure. Therefore, the formed market price does not contain all relevant information, which leads to market distortions and thus a loss of social welfare (Sturm and Vogt, 2018).

This study cannot, however, answer the question of the likelihood of such prices being implemented in practice. There have been campaigns for eco-labelling or even for the display of true prices in supermarkets (Michalke et al., 2022). Sensible measures to adjust market prices accordingly, for example by introducing meat or nitrogen taxes, are part of the current scientific discourse (Funke et al., 2022; Meyer-Aurich et al., 2020). However, consumers' understanding and acceptance is crucial yet currently lacking (Feucht and Zander, 2018). Furthermore, policymakers need to follow the scientific consensus in order to advance agricultural systems sustainably.

Lastly, the reflection on agricultural externalities necessitates a discourse on whether the presented approach would lead to an abuse of natural capital rather than its conservation, and on the ethics of putting a price on the environment: pollution would be allowed to those who can afford it, adding another social dimension to the assessed issue. This needs to be addressed in future socio-political research. Nevertheless, the pursuit of environmentally and socially conscious consumption and production is an important route towards a more sustainable global future. The approach presented here contributes to the development of economic incentives and policies for sustainable behavior in the food sector.

4.3. Assumptions and limitations

In addition to the addressed uncertainties, the results are subject to assumptions and limitations within the LCA and TCA approaches. The temporal boundaries of the system do not allow to include the effects of crop rotation, since it is assumed that input factors are used for the cultivation of a single crop on the utilized agricultural area. In reality, land is used to cultivate several crops over a given period of time. Therefore, apparent advantages of soil properties or nutrient supply from a biodiverse crop rotation are not considered. Moreover, elementary flows representing no more than 2% of the cumulative mass and energy flows are cut off according to the documentation of AFP 5.0. Furthermore, while we find that manure has a significant impact on the overall results, manure use is not precisely allocated to each product, but generally distributed over the average livestock density per hectare. We would like to emphasize that this is a rather theoretical approach to modeling manure application, which may underestimate results for products produced in livestock-dense regions, where it is likely that more manure is used for crop production in the vicinity. In turn, the approach may overestimate results for products or regions that rely less on manure for fertilization. It should be noted that this contributes to the uncertainty of the results. In addition, we used the assumption that organic feed is produced only on site or in the region, which might underestimate the impacts from land transformation that may occur during feed production in other regions. This underestimation, however, is likely to be small as it only affects *land use* and, to a lesser extent, *global warming* (cf. Fig. 3). Lastly, despite our attempts to use different pricing scenarios, the monetization of environmental impacts remains highly subjective and thus biased (Ekardt and Henning, 2015; Hansjürgens, 2015). This also includes supposed market effects in the form of lower sales volumes due to price-sales interrelations, which cannot be represented in this assessment.

4.4. Outlook for future research

It should be noted that beneficial ecosystem services (ES), such as regulating and maintaining soil functions (Sandhu et al., 2010), are not yet accounted for in LCA and TCA. Since organic production tends to result in lower output of produce but higher ES (Boone et al., 2019), the inclusion of ES in the assessment of farming practices has the potential to shift in favor of organic produce. The midpoint of land use, for example, strongly influences the damage to ecosystem quality. Within this midpoint (or endpoint, respectively), the quality of used land is not considered, even though this could have a positive impact on the actual ecosystem quality, e.g., with higher biodiversity as is likely in organically managed land (Mueller et al., 2014; Tuck et al., 2014). Approaches to include ES in LCA have been proposed (Alejandre et al., 2019; Rugani et al., 2019; Zhang et al., 2010), but this has been applied to the agricultural context only scarcely (e.g., Boone et al., 2019).

Furthermore, food analyses need to emphasize the variability of farming systems (e.g., manure handling or feedstock imports), which, as our results show, can significantly influence environmental performance. A greater emphasis on primary data collection would render modeling approaches more realistic. Literature argues, for example, that the product-based approach with impacts per unit of product generally favors intensive, high-yield practices and underrepresents the positive aspects of more gentle approaches (van der Werf et al., 2020). Therefore, functional units other than the prevalent product-based approach should be explored (e.g., per unit of profit, or per caloric value). In particular, a nutrition-focused assessment would allow for a more nuanced comparison between products, address the conflict between nutritional and environmental aspects, and render the communication of the results more intricate. Appendix A10 therefore also provides the caloric value of all products (in kilocalories).

Another aspect that highly influences food systems are agricultural subsidies. In 2019, German agricultural sales amounted to almost 40 billion Euros, while EU subsidies of 6.7 billion Euros were paid (BMEL, 2020). This illustrates the large impact that subsidies have on the market. Even though agricultural subsidies become increasingly decoupled from specific commodity production, commodity-specific support measures remain a significant part of agricultural subsidies (OECD, 2022). Although Common Agricultural Policy (CAP), the dominating subsidies program in all EU countries, is slowly introducing instruments to support environmentally sustainable production (European Commission, 2022), current commodity-specific support measures are not aligned with environmental burdens, leading to an unsustainable support system (Pe'er et al., 2019). Springmann and Freund (2022) analyze options for reforming agricultural subsidies in line with health and climate change objectives, and present data on commodity-specific subsidies. While current commodity-specific subsidies for, e.g., the food groups cereals, meat and milk, are subsidized in a similar range (between 21% and 25% of producer prices) (cf. Appendix A12), the externalities of these product groups vary drastically (conventional cereals 0.41 €/kg, milk, 0.75 €/kg, and meat 4.42 €/kg). This underpins the demand for a CAP reform, as stated by Pe'er et al. (2019), that is aligned with the environmental and societal burdens caused by the subsidized commodities.

The presented method for calculating the true costs of food can also be applied to other countries. The results are likely to change, based on the production data and practices observed. General notions, however, can be translated (as seen in, e.g., Poore and Nemecek, 2018): fewer externalities are generated by less complex production chains, like plant-based production, and less extensive practices.

5. Conclusion

This study assesses environmental damage economically: in a True Cost Accounting (TCA) case study on 22 agricultural products in Germany, we combine the LCA-based environmental assessment of organically and conventionally produced food products with the internalization of their monetary, societal impacts.

We find that, on average (unweighted), plant-based products from conventional systems cause externalities of about €0.79 per kg, and those from organic production of about €0.42 per kg. Conventional and organic meat (beef, pork, poultry) production generates, on average, external costs of €4.42 and €4.22 per kg (liveweight), respectively, with beef generating the highest costs of all categories. Milk and eggs from conventional farming generate costs of about €1.29 per kg, while their organic counterparts generate €1.10 per kg on average. The externalities of organic production (base case) are lower than their conventional counterparts for all categories except beef cattle (when sourced exclusively from beef cattle, cf. Appendix A5, Figure S1-16). We also find that the results are highly sensitive to organic manure application and the yield per hectare or animal, as well as to the underlying monetization method.

When accounting for the fact that current producer prices for organic products are disproportionally higher than for conventional products, the “true prices” (market price + external costs) of organic products are not lower than those of conventional products. The lower agricultural yields in organic systems also contribute to this assessment, as they partially offset the environmental benefits that organic produces have over their conventional counterparts. Nevertheless, it can be noted that the internalization of external costs leads to an alignment of the prices of the two production practices, thus correcting to some degree the current market distortions, especially for cereals, most oilseeds, and most animal-based commodities.

This study provides a unique dataset for comparing different production methods at the country level. The strengths of this study lie in the combination of the scientific perspective through LCA and the economic perspective through TCA. The LCA results alone reveal 1) a strong influence of dietary behavior. Meat- and dairy-based foods lead to considerably higher externalities than plant-based foods, regardless of the production method; and 2) confirm the favorability of organic products compared to conventional production methods. Monetizing impacts using TCA bridges the gap between research and practice. The monetization of impacts is designed to raise public awareness and strengthen the hand of policymakers who recognize that solutions are needed for a sustainable transition of the agri-food sector.

Financial disclosure

The project on which this report is based was funded by the German Federal Ministry of Education and Research within the Research Initiative for the Conservation of Biodiversity (FEdA) under the funding code 01UT2108A. The responsibility for the content of this publication lies with the author.

CRediT authorship contribution statement

Amelie Michalke: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Sandra Köhler:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lukas Messmann:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Andrea Thorenz:** Validation, Writing – review & editing, Resources, Supervision. **Axel Tuma:** Validation, Resources, Supervision. **Tobias Gaugler:** Conceptualization, Validation, Writing – review & editing, Supervision.

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

The electronic Supporting Information S2 is shared in a data repository: 10.5281/zenodo.6477072.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137134.

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