# True cost accounting of organic and conventional food production

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This supporting information SI-1 provides background information on assessed foodstuff (A1), scope of the assessment (A2), Life Cycle Inventories (A3), and Life Cycle Impact Assessment (A4), as well as comprehensive assumptions and results of TCA (A5) and the sensitivity analysis (A6).

**Content**

## Appendix A1 Assessed foodstuff

**Table S1-1.** List of assessed foodstuff by category and food group

| Category | Food group | Name |
|---|---|---|
| plant-based | cereals | Barley |
| plant-based | cereals | Maize |
| plant-based | cereals | Oat |
| plant-based | cereals | Rye |
| plant-based | cereals | Triticale |
| plant-based | cereals | Wheat |
| plant-based | legumes | Beans, broad |
| plant-based | legumes | Beans, green |
| plant-based | legumes | Soybean |
| plant-based | legumes | Lupine |
| plant-based | oilseeds | Mustard seed |
| plant-based | legumes | Pea |
| plant-based | oilseeds | Linseed |
| plant-based | oilseeds | Rapeseed |
| plant-based | oilseeds | Sunflower seed |
| plant-based | roots | Potato |
| plant-based | roots | Beets |
| animal | porcine | Pork |
| animal | poultry | Poultry |
| animal | bovine | Beef |
| animal-based | bovine | Milk |
| animal-based | poultry | Eggs |

### Appendix A2 System boundaries & functional unit

The system boundary for the comparative LCAs of organic and conventional foodstuff production is cradle-to-farmgate in Germany. All products are assessed per kg of product. Life cycle inventories from the Agri-Footprint (AFP) 5.0 database (van Paassen et al., 2019a) are used for foodstuff production in the conventional base case (cf. Table 1 in Manuscript). 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). The arable crop production system comprises field cultivation, production. The production systems of all foodstuffs include manufacturing of all material inputs such as seeds, feed, fertilizers, and pesticides and transporting of all such inputs to the farm with its related emissions. Additionally, the production and combustion of heat and electric energy, and fuel is considered. Farm infrastructure is only considered for plant-based production and hence only indirectly included in animal-based production through the feed. However, capital goods (e.g., stables) are excluded from animal-based production as modeled in the AFP database by default. We acknowledge how this might skew the results to some degree. Production processes for Germany were selected, except for animal production, where only processes for the Netherlands (pork, poultry, eggs, milk) and Ireland (beef) are available. We deemed these sufficient for the purpose of this paper, as legislative conditions are well comparable (all part of EU), and all lie in the same climate zone (middle latitude) as Germany. We adjust, however, transport distances and feed input to fit the German scope.

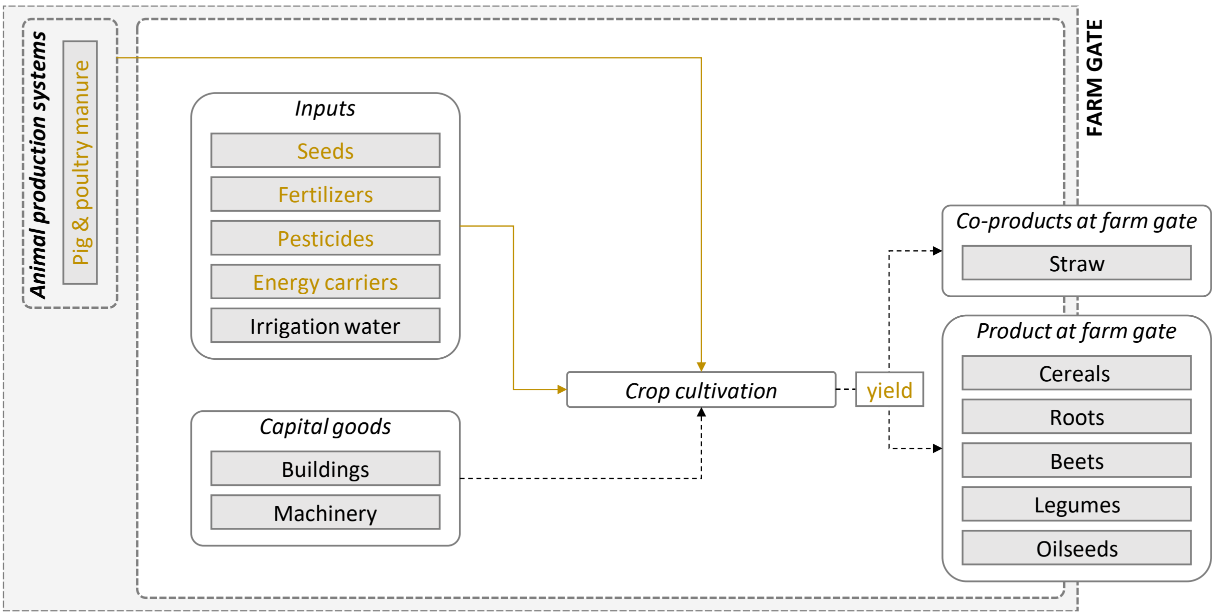


**Figure S1-1.** System boundaries of plant-based production systems. Elements in yellow are adjusted for organic systems compared to the conventional base case. Drawn lines represent transport processes, while dashed lines are inputs without explicit transport.

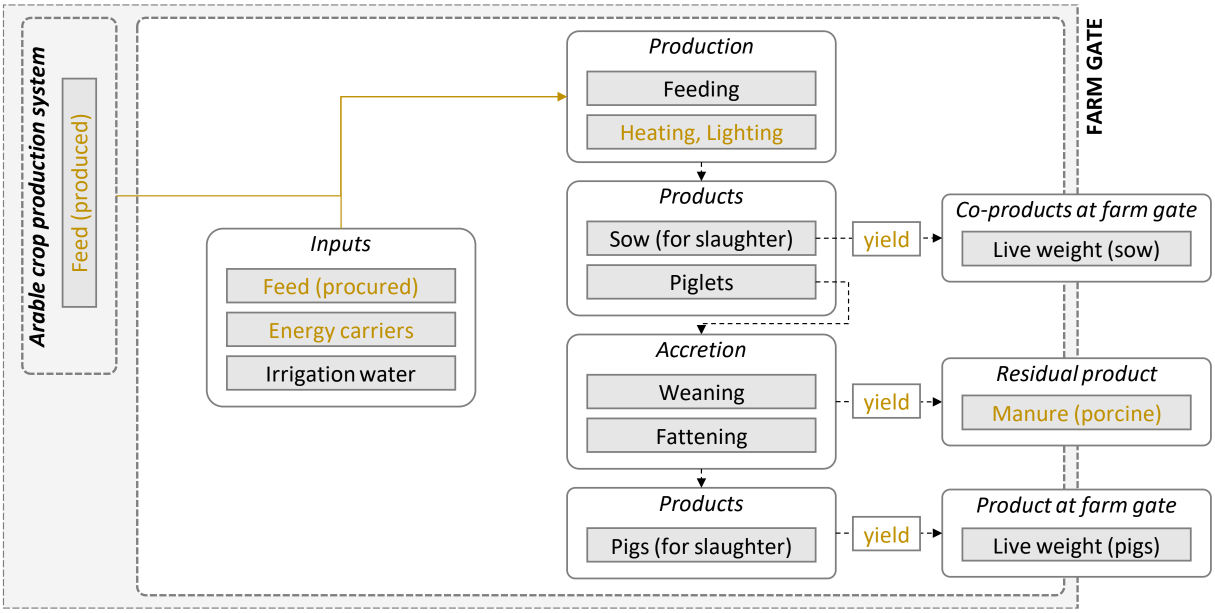


**Figure S1-2.** System boundaries of animal production systems. Elements in yellow are adjusted for organic systems compared to the conventional base case. Drawn lines represent transport processes, while dashed lines are inputs without explicit transport.

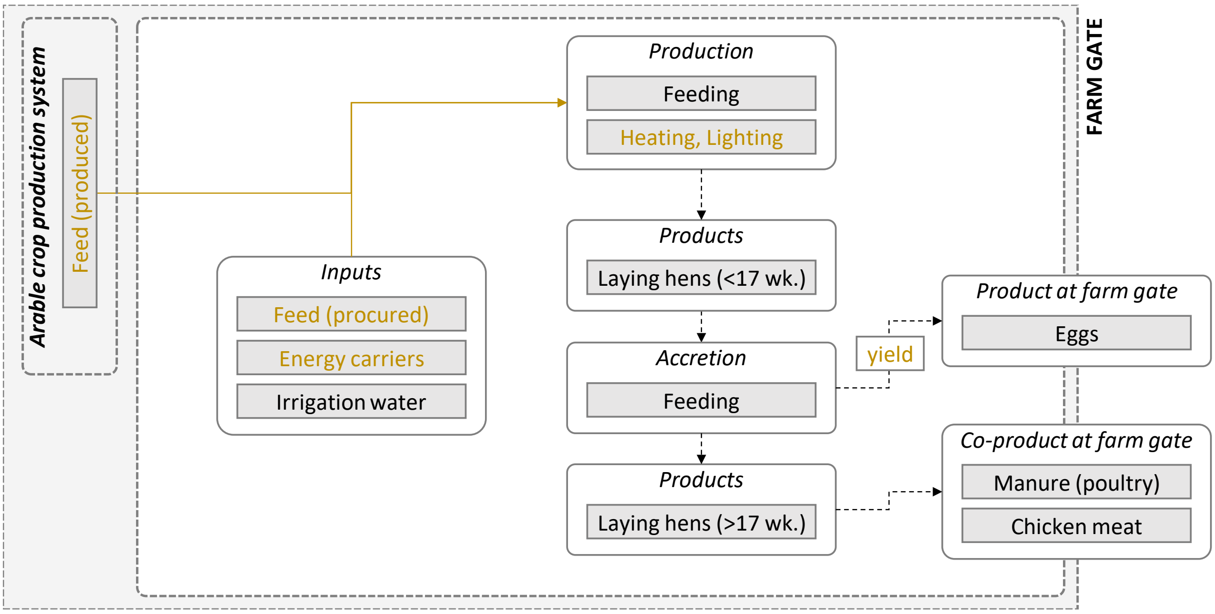


**Figure S1-3.** Exemplary system boundaries (here: eggs) of animal-based production systems. Elements in yellow are adjusted for organic systems compared to the conventional base case. Drawn lines represent transport processes, while dashed lines are inputs without explicit transport. (Abbreviations: wk. = weeks)

**Appendix A3 Life Cycle Inventories**

**Emissions to air, groundwater, and soil**

The adjustments of yield, manure, fertilizers and pesticides within organic scenarios in turn lead to changes in the direct and indirect emissions to air, groundwater, and soil of heavy metals, carbon and nitrogen compounds, phosphorous, fungicides, and plant growth regulators. The calculation method is based on the documentation of Agri-Footprint 5.0 (van Paassen et al., 2019a). The emissions are calculated for all crops $C$ in scenario $S$, including the conventional base case. The parameters, as used in the LCIs (Supporting Information S2, Appendix A9), are then given relative to the conventional base case. The calculations themselves are given in Appendix A8 of Supporting Information S2.

For each crop $c \in C$, scenario $s \in S$, and the seven heavy metals $I$ (Cd, Cr, Cu, Hg, Ni, Pb, Zn), soil emissions $E_{s,c,i}^{hm,soil}$ (Eq. 1) of heavy metal $i \in I$ are calculated as heavy metal inputs (from application of fertilizers $F$ and manure types $M$ in the LCI, and from atmospheric deposition) minus heavy metal outputs (leach to water and heavy metal uptake from biomass), multiplied with a crop- and metal-specific allocation factor $\alpha_{s,c,i}$ (the share of agricultural inputs in the total inputs, Eq. 3). The Agri-Footprint 5.0 database does not include heavy metal inputs from seeds, and only includes heavy metal uptake by the grain (i.e., it is assumed that the co-product straw is fully incorporated into the soil), although it also gives removal ratios. After discussing this with the authors of the Agri-Footprint database, we decided on including both seed inputs and straw uptake in the calculation, and thus determine the emissions of conventional foodstuff ourselves, and adjusting the underlying original inventories accordingly. Heavy metal emissions to water $E_{s,c,i}^{hm,water}$ (Eq. 2) of heavy metal $i \in I$ is calculated as the annual average amount of heavy metal leaching to groundwater times the allocation factor.

$$E_{s,c,i}^{hm,soil} = \left(\sum_{f \in F} i_{s,c,f} h_{i,f} + \sum_{m \in M} i_{s,c,m} h_{i,m} + \sum_{m \in M} i_c^{seed} h_{i,c} - l_i - y_{s,c} h_{c,i}\right) \cdot \alpha_{s,c,i} \quad \forall s \in S, c \in C, i \in I \quad (1)$$

$$E_{s,c,i}^{hm,water} = l_i \cdot \alpha_{s,c,i} \quad \forall s \in S, c \in C, i \in I \quad (2)$$

$$\alpha_{s,c,i} = \frac{\sum_{f \in F} i_{s,c,f} h_{i,f} + \sum_{m \in M} i_{s,c,m} h_{i,m} + \sum_{m \in M} i_c^{seed} h_{i,c}}{\sum_{f \in F} i_{s,c,f} h_{i,f} + \sum_{m \in M} i_{s,c,m} h_{i,m} + \sum_{m \in M} i_c^{seed} h_{i,c} + d_i} \quad \forall s \in S, c \in C, i \in I \quad (3)$$

with

| | | |
|---|---|---|
| $i_{s,c,f}$ | annual input of fertilizer $f \in F$ for the cultivation of crop $c \in C$ in scenario $s \in S$ | in kg/ha |
| $h_{i,f}$ | content of heavy metal $i \in I$ in fertilizer $f \in F$ | in mg/kg |
| $i_{s,c,m}$ | annual input of manure $m \in M$ for the cultivation of crop $c \in C$ in scenario $s \in S$ | in kg dry matter/ha |
| $h_{i,m}$ | content of heavy metal $i \in I$ in manure $m \in M$ | in mg/kg dry matter |
| $i_c^{seed}$ | annual input of seeds for the cultivation of crop $c \in C$ | in kg dry matter/ha |
| $d_i$ | annual amount of atmospheric deposition of heavy metal $i \in I$ | in mg/ha |
| $l_i$ | annual average leaching to groundwater of heavy metal $i \in I$ | in mg/ha |
| $y_{s,c}$ | annual yield (grain + straw) of crop $c \in C$ in scenario $s \in S$ | in kg dry matter/ha |
| $h_{i,c}$ | content of heavy metal $i \in I$ in biomass (grain) of crop $c \in C$ | in mg/kg dry matter |

The ban of most fertilizers in the organic crop cultivation (see section 2.2.2) leads to significantly smaller heavy metal inputs from fertilizers. This is, to some degree, counterbalanced by increased manure application in scenario O4, and by a reduced heavy metal uptake due to the smaller yields compared to conventional crop cultivation in all organic scenarios (see section 2.2.1).

Furthermore, air, groundwater, and soil emissions of fungicides and plant growth regulators are zeroed in the organic crop systems due to their exclusion as described in section 2.2.2. Direct and indirect (volatilization and leaching) emissions of dinitrogen oxide ($N_2O$, to air) and nitrate ($NO_3^-$, to water) from crop residues are unchanged compared to the conventional system. Adjustments to dinitrogen oxide ($N_2O$, direct and indirect, to air), ammonia ($NH_3$, to air), nitrate ($NO_3^-$, to water), and phosphorous (to water) emissions due to the use of manure are proportional to the manure use within the different scenarios (section 2.2.1).

Emissions from the use of fertilizers are subject to the list of allowed and banned fertilizers, as described in section 2.2.1. Limestone is allowed, while the rest of the synthetic fertilizers is banned in the organic scenarios. Emissions include carbon dioxide ($CO_2$) emissions to air ($E_{s,c}^{co2}$, Eq. 4), direct and indirect nitrous oxide ($N_2O$) emissions to air ($E_{s,c}^{f,n2o(d)}$ and $E_{s,c}^{f,n2o(i)}$, Eqs. 5 and 6), ammonia ($NH_3$) emissions to air ($E_{s,c}^{f,nh3}$, Eq. 7), nitric oxide (NO) emissions to air ($E_{s,c}^{f,no}$, Eq. 8), nitrate ($NO_3^-$) emissions to water ($E_{s,c}^{f,no3-}$, Eq. 9), and phosphorus emissions to water ($E_{s,c}^{f,p}$, Eq. 10). Emissions from manure are subject to the amount of manure applied in the respective organic scenario, as described in section 2.2.1. They include direct and indirect nitrous oxide ($N_2O$) emissions to air ($E_{s,c}^{m,n2o(d)}$ and $E_{s,c}^{m,n2o(i)}$, Eqs. 11 and 12), ammonia ($NH_3$) emissions to air ($E_{s,c}^{m,nh3}$, Eq. 13), nitrate ($NO_3^-$) emissions to water ($E_{s,c}^{m,no3-}$, Eq. 14), and phosphorus emissions to water ($E_{s,c}^{m,p}$, Eq. 15).

The re-calculations for the organic scenarios follow the specifications documented by the AgriFootprint 5.0 database and is carried out for each crop $c \in C$ in each scenario $s \in S$. C, N and P emissions in AgriFootprint's inventories are 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) − for the study at hand, we update both the conventional and the organic calculations of N emissions based on updated and/or disaggregated N-related emission factors in the 2019 refinement (IPCC, 2019) of the 2006 IPCC guidelines.

$$E_{s,c}^{co2} = \sum_{f\in F} i_{s,c,f} c^{co2} e_f^{co2} \quad \forall s \in S, c \in C \quad (4)$$

$$E_{s,c}^{f,n2o(d)} = \sum_{f\in F} i_{s,c,f} s_f^n c^{n2o} e^{f,n2o(d)} \quad \forall s \in S, c \in C \quad (5)$$

$$E_{s,c}^{f,n2o(i)} = \sum_{f\in F} i_{s,c,f} s_f^n c^{n2o} \left(e^{n2o(v)} e_f^{f,nh3(v)} + e^{n2o(l)} e^{no3(l)}\right) \quad \forall s \in S, c \in C \quad (6)$$

$$E_{s,c}^{f,nh3} = \sum_{f\in F} i_{s,c,f} s_f^n c^{nh3} e_f^{f,nh3} \quad \forall s \in S, c \in C \quad (7)$$

$$E_{s,c}^{f,no} = \sum_{f\in F} i_{s,c,f} s_f^n e^{f,no} \quad \forall s \in S, c \in C \quad (8)$$

$$E_{s,c}^{f,no3-} = \sum_{f\in F} i_{s,c,f} s_f^n c^{no3} e^{no3} \quad \forall s \in S, c \in C \quad (9)$$

$$E_{s,c}^{f,p} = \sum_{f\in F} i_{s,c,f} s_f^{p2o5} c^p e^{f,p} \quad \forall s \in S, c \in C \quad (10)$$

$$E_{s,c}^{m,n2o(d)} = \sum_{m\in M} i_{s,c,m} s_m^n c^{n2o} e^{m,n2o(d)} \quad \forall s \in S, c \in C \quad (11)$$

$$E_{s,c}^{m,n2o(i)} = \sum_{m\in M} i_{s,c,m} s_m^n c^{nh3} \left(e^{n2o(v)} e^{m,nh3(v)} + e^{n2o(l)} e^{no3(l)}\right) \quad \forall s \in S, c \in C \quad (12)$$

$$E_{s,c}^{m,nh3} = \sum_{m\in M} i_{s,c,m} s_m^n c^{nh3} e^{m,nh3(v)} \quad \forall s \in S, c \in C \quad (13)$$

$$E_{s,c}^{m,no3-} = \sum_{m\in M} i_{s,c,m} s_m^n c^{no3} e^{no3(l)} \quad \forall s \in S, c \in C \quad (14)$$

$$E_{s,c}^{m,p} = \sum_{m\in M} i_{s,c,m} s_m^{p2o5} c^p e^{m,p} \quad \forall s \in S, c \in C \quad (15)$$

with [1][2]

| | | |
|---|---|---|
| $i_{s,c,f}$ | annual input of fertilizer $f \in F$ for the cultivation of crop $c \in C$ in scenario $s \in S$ | in kg/ha |
| $i_{s,c,f}$ | annual input of manure $m \in M$ for the cultivation of crop $c \in C$ in scenario $s \in S$ | in kg/ha |
| $e_f^{co2}$ | $CO_2$ emission factor of fertilizer $f \in F$ | in kg emitted/kg applied |
| $e^{f,n2o(d)}$ | $N_2O$ emission factor (direct) for synthetic fert. (*$EF_1$*) [3] | in kg emitted/kg applied |
| $e^{m,n2o(d)}$ | $N_2O$ emission factor (direct) for organics (manure) (*$EF_1$*) [3] | in kg emitted/kg applied |
| $e^{n2o(v)}$ | $N_2O$ emission factor (indirect, volatized) (*$EF_4$*) [3] | in kg emitted/kg volat. |
| $e^{n2o(l)}$ | $N_2O$ emission factor (indirect, leached) (*$EF_5$*) [3] | in kg emitt./kg leached |
| $e_f^{f,nh3(v)}$ | fraction of synthetic fertilizer $f \in F$ that volatilizes as $NO_x$/$NH_3$ (*$Frac_{GASF}$*) [3] | in kg volatized/kg applied |
| $e^{m,nh3(v)}$ | fraction of organic fertilizer (manure) that volatilizes as $NO_x$/$NH_3$ (*$Frac_{GASM}$*) [3] | in kg volatized/kg applied |
| $e_f^{f,nh3}$ | NH3 emission factor (Tier 2) of fertilizer $f \in F$ | in kg emitted/kg applied |
| $e^{no}$ | NO emission factor | in kg emitted/kg applied |
| $e^{no3(l)}$ | fraction that leaches as $NO_3^-$ (*$Frac_{LEACH}$*) [3] | in kg emitted/kg applied |
| $e^{f,p}$ | phosphorous emission factor (fertilizer) | in kg emitted/kg applied |
| $e^{m,p}$ | phosphorous emission factor (manure) | in kg emitted/kg applied |
| $c^{co2}$ | Carbon to $CO_2$ conversion factor | in u/u |
| $c^{n2o}$ | Nitrogen to $N_2O$ conversion factor | in u/u |
| $c^{nh3}$ | Nitrogen to $NH_3$ conversion factor | in u/u |
| $c^{no3}$ | Nitrogen to $NO_3^-$ conversion factor | in u/u |
| $c^p$ | $P_2O_5$ to phosphorous conversion factor | in u/u |
| $s_f^n$ | share of nitrogen in fertilizer $f \in F$ | in kg/kg |
| $s_m^n$ | share of nitrogen in manure $m \in M$ | in kg/kg |
| $s_f^{p2o5}$ | share of phosphorous pentoxide ($P_2O_5$) in fertilizer $f \in F$ | in kg/kg |
| $s_m^{p2o5}$ | share of phosphorous pentoxide ($P_2O_5$) in manure $m \in M$ | in kg/kg |

[1] Calculation and parameter values are provided in detail in Supporting Information S2 for each crop in each scenario.
[2] Given in Supporting Information S2.
[3] *$EF_1$*, *$EF_4$*, *$EF_5$*, *$Frac_{GASF}$*, *$Frac_{GASM}$*, *$Frac_{LEACH}$* are the denominators as used in AgriFootprint 5.0 and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

The actual parameters, as used in the Life Cycle Inventories (Appendix A9) are calculated as the ratio between the emissions in different organic scenarios and the conventional base case (C). For example, in the organic base case (O), $S\_Cd\_Barley$ (cadmium emissions to soil for barley; cf. Appendix A8) are calculated as follows:

$$S\_Cd\_Barley = \frac{E_{O,barley,Cd}^{hm,soil}}{E_{C,barley,Cd}^{hm,soil}}$$

Since synthetic fertilizers are banned in the organic scenarios, emissions of nitrogen compounds from synthetic fertilizers are always zero in the organic scenarios. Furthermore, nitrogen compound emissions from manure vary uniformly with the amount of nitrogen in the applied amount of manure, and all plant-based products have the same amount of applied manure in the Life Cycle Inventories of Agri-Footprint 5.0. Hence, the parameter $N\_man$ (cf. Appendix A8) is identical for all nitrogen compounds and all products, and only varies with the scenario. E.g., for the organic base case (O):

e.g., $N\_man = \frac{E_{O,barley}^{m,n2o(d)}}{E_{C,barley}^{m,n2o(d)}} = \frac{E_{O,potatoes}^{m,n2o(d)}}{E_{C,potatoes}^{m,n2o(d)}}$ and $N\_man = \frac{E_{O,barley}^{m,n2o(d)}}{E_{C,barley}^{m,n2o(d)}} = \frac{E_{O,barley}^{m,n2o(i)}}{E_{C,barley}^{m,n2o(i)}} = \frac{E_{O,barley}^{m,nh3}}{E_{C,barley}^{m,nh3}} = \frac{E_{C,barley}^{m,no3-}}{E_{C,barley}^{m,no3-}}$

Finally, some LCI values are modified by *Correction Factors* (*CFs*; see Appendix 8) for both conventional and organic systems. This is mainly the case for the aforementioned updates to N-related emission factors according to the 2019 refinement (IPCC, 2019) of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and partially for inconsistencies between our calculation of heavy metal emissions and the values in the LCIs, which have been discussed with the authors of AgriFootprint 5.0. The Correction Factors calculate as the ratio between the emission values in the conventional system as calculated by us and as provided in the LCI by AgriFootprint 5.0:

e.g., $N2Od\_fert\_CF_{barley} = \frac{E_{C,barley}^{f,n2o(d)}}{E(AFP5.0)_{C,barley}^{f,n2o(d)}} = 1.6$

**Literature analysis**

Literature used in the comprehensive meta-analysis on environmental impacts of organic and conventional production by Meier et al. (2015) was complemented with forward and backward search and a systemic keyword search. As a result, 48 comparative LCA studies serve as the basis for parameter definition of organic production in this paper (see Supporting Information S2, Appendix A7(a)). Since the yield influences all production processes, it is a crucial parameter in comparative LCAs. We therefore extend the literature analysis and conduct a specific search to identify yield differences between organic and conventional production. As a starting point we use extensive meta-analyses by de Ponti et al. (2012), Ponisio et al. (2015), Seufert et al. (2012). As a result, we identify a total of 28 studies concerning yield differences (see Supporting Information S2, Appendix A7(b)).

**Manure application**

In AFP 5.0, the amount of manure applied per hectare is the same for all plant-based products since its calculation is based on the underlying country's average livestock density per hectare. This procedure implies that all manure produced is also discharged in conventional and organic systems. For the organic base case, we adjust manure values according to the reported organic (Eurostat, 2020c; Eurostat, 2020d) compared to the conventional (Eurostat, 2020a; Eurostat, 2020b; Eurostat 2020c) livestock density in Germany. This is a simplification of reality for two reasons: First, manure use varies significantly between different regions according to the prevailing livestock density, which is not consistent over all of Germany. Second, organic farms are allowed to import manure from conventional farms, if they are not factory farms (more than 2.5 large animal units per ha). The second point is accounted for in scenarios O3 and O4, where organic agriculture uses more manure than is produced under organic conditions. The first point is not accounted for in this study and likely underestimates emissions from manure for products from regions with high livestock density and overestimates products from no- or low-manure input.

In Germany's total organic area, organically raised livestock is smaller than in the conventional livestock system. This fact results in pig manure use of 9.57% and poultry manure use of 54.41% compared to conventional farming modeled in C. This is based on a model of (Vellinga et al., 2013). Authors of AFP 5.0 do concede that the actual manure use will likely also depend on the specific crop's needs and availability of the manure. Nevertheless, this assumption is justified with the following: "[…] since application of manure will be of benefit to arable soil for a number of years and cropping cycles (as it releases nutrients relatively slowly), this average manure application rate is maintained/justified" (van Paassen et al., 2019b). To stay in line with the methodology used for the conventional base case and optimize comparability, we transfer these assumptions and modelling rules from AFP 5.0 to our organic base case. Since organic production has stricter limitations regarding the number of animals allowed per hectare, less manure will also be accrued per hectare, hence the rather low amounts per unit. Transportation of manure is considered with 30km transported distance, which depicts the average transportation distance for balancing out between manure-rich and -poor areas.

However, some studies report additional manure application in organic systems to achieve sufficient nutrient supply of soil and crops (de Backer et al., 2009; Nemecek et al., 2011). The studies register a higher use of manure in organic than in conventional systems to compensate for the lack of the not allowed synthetic fertilizer (cf. 2.2.2). We identify six studies reporting differences in manure application between both production systems. The limited data points do not allow for modeling product or type of livestock-specific manure application rates; therefore, we include different scenarios for manure application in the sensitivity analysis (see section 2.4).

## Appendix A4 Life Cycle Impact Assessment

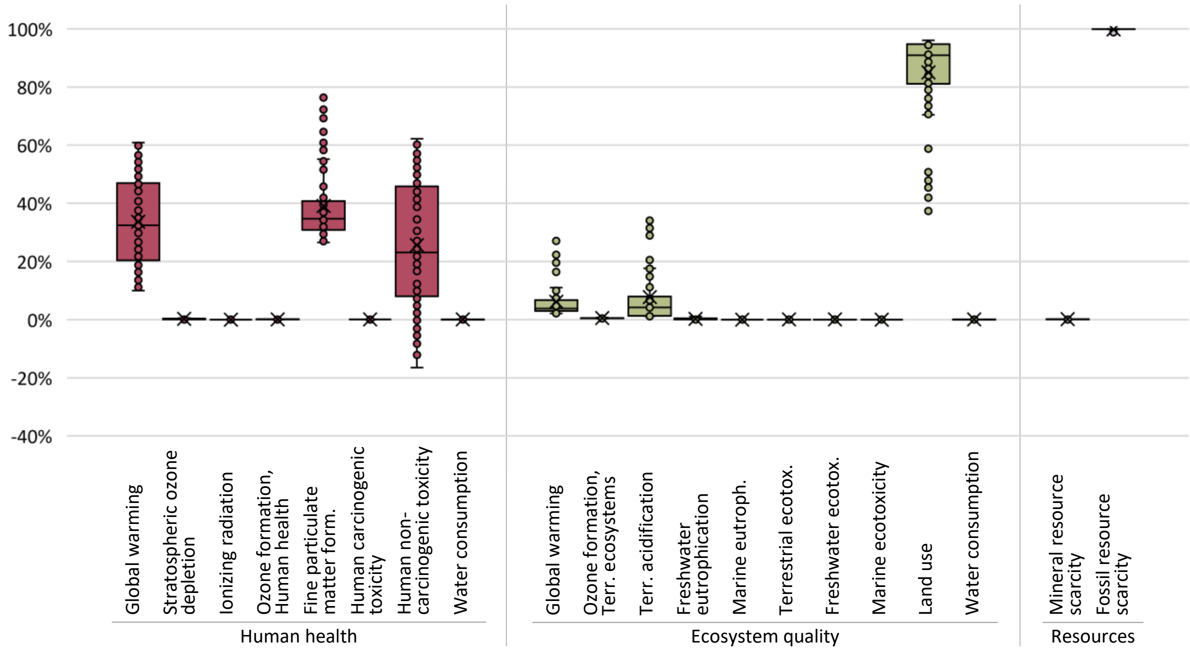


**Figure S1-4.** ReCiPe midpoint to endpoint contributions over all products and scenarios

**Table S1-2.** ReCiPe midpoint to endpoint factors (according to Huijbregts et al. 2017)

| Impact category / midpoint | Impact unit | Endpoint aggregation | Midpoint-to-endpoint factor |
|---|---|---|---|
| Global warming | kg $CO_2$ eq | E1 & E2 | 9.28E-07 & 2.80E-09 |
| Stratospheric ozone depletion | kg CFC11 eq | E1 | 5.31E-04 |
| Ionizing radiation | kBq Co-60 eq | E1 | 8.50E-09 |
| Ozone formation, Human health | kg $NO_x$ eq | E1 | 9.10E-07 |
| Fine particulate matter formation | kg PM2.5 eq | E1 | 6.29E-04 |
| Ozone formation, Terrestrial ecosystems | kg $NO_x$ eq | E2 | 1.29E-07 |
| Terrestrial acidification | kg $SO_2$ eq | E2 | 2.12E-07 |
| Freshwater eutrophication | kg P eq | E2 | 6.71E-07 |
| Marine eutrophication | kg N eq | E2 | 1.70E-09 |
| Terrestrial ecotoxicity | kg 1,4-DCB | E2 | 1.14E-11 |
| Freshwater ecotoxicity | kg 1,4-DCB | E2 | 6.95E-10 |
| Marine ecotoxicity | kg 1,4-DCB | E2 | 1.05E-10 |
| Human carcinogenic toxicity | kg 1,4-DCB | E1 | 3.32E-06 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | E1 | 2.28E-07 |
| Land use | $m^2$a crop eq | E2 | 8.88E-09 |
| Mineral resource scarcity | kg Cu eq | E3 | 2.31E-01 |
| Fossil resource scarcity | kg oil eq | E3 | 4.57E-01 |
| Water consumption | $m^3$ | E1 & E2 | 2.22E-06 & 6.04E-13 |

| Tag | Area of protection / endpoint | Damage unit |
|---|---|---|
| E1 | Human health | DALY |
| E2 | Ecosystem quality | Species.yrs |
| E3 | Resource scarcity | USD2013 |

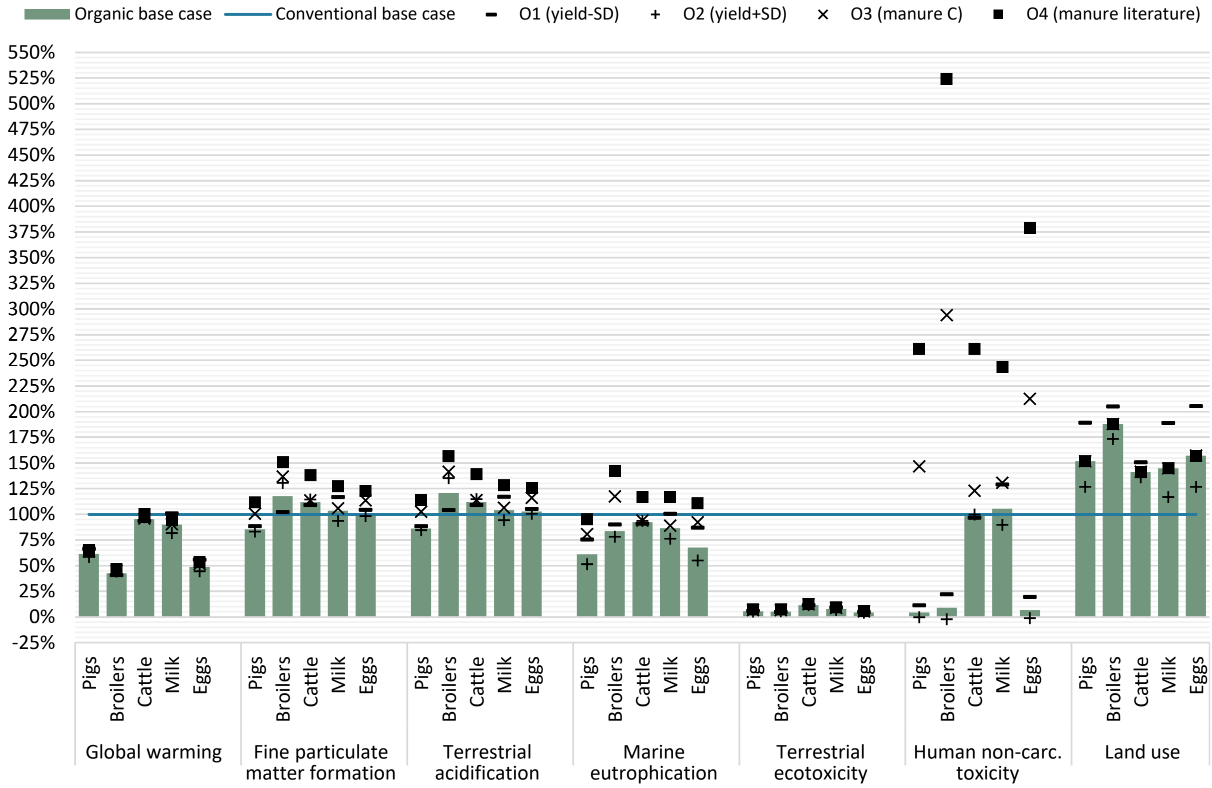


**Figure S1-5.** ReCiPe midpoints for animal-based foodstuff with organic scenarios (O) compared to the conventional base case (C) and influence of yield and manure.

Figure S1-5 shows the environmental impacts of organic animal-based foodstuff 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 case vary for every product in absolute values.

Equivalent to the plant-based products, *land use* shows no benefit for organic production since this impact category is foremost influenced by the yield per ha of feed production, which is consistently lower for all organic plant-based products. Within the midpoint of *human non-carcinogenic toxicity*, only organic milk and beef result in impacts comparable to conventional production. This is because both beef and dairy cattle consume, in addition to i.a. compound feed, grass (at least within the modelling approach of AFP 5.0), which is associated with a lot of manure use relevant to this category. Benefits of organic production are most pronounced for the *midpoint terrestrial ecotoxicity*, due to the avoidance of plant protection in conventional feed production. In addition, results for *global warming* show an emission reduction for organic compared to conventional produce, with the exception of milk in scenario O2 and cattle in scenario O4. Considering the midpoints *fine particulate matter formation* and *terrestrial acidification,* organic production is not as beneficial compared to plant-based products. The reason for this lies primarily in the longer lifespan of animals in organic systems.

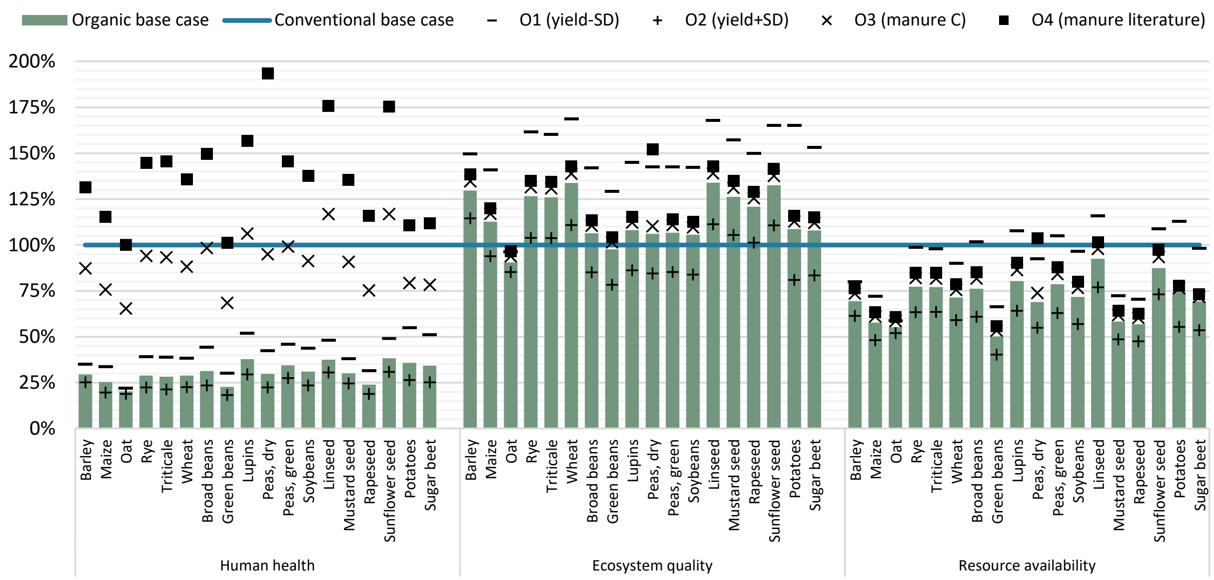


**Figure S1-6.** ReCiPe endpoints for plant-based foodstuff with organic scenarios (O) compared to the conventional base case (C) and influence of yield and manure.

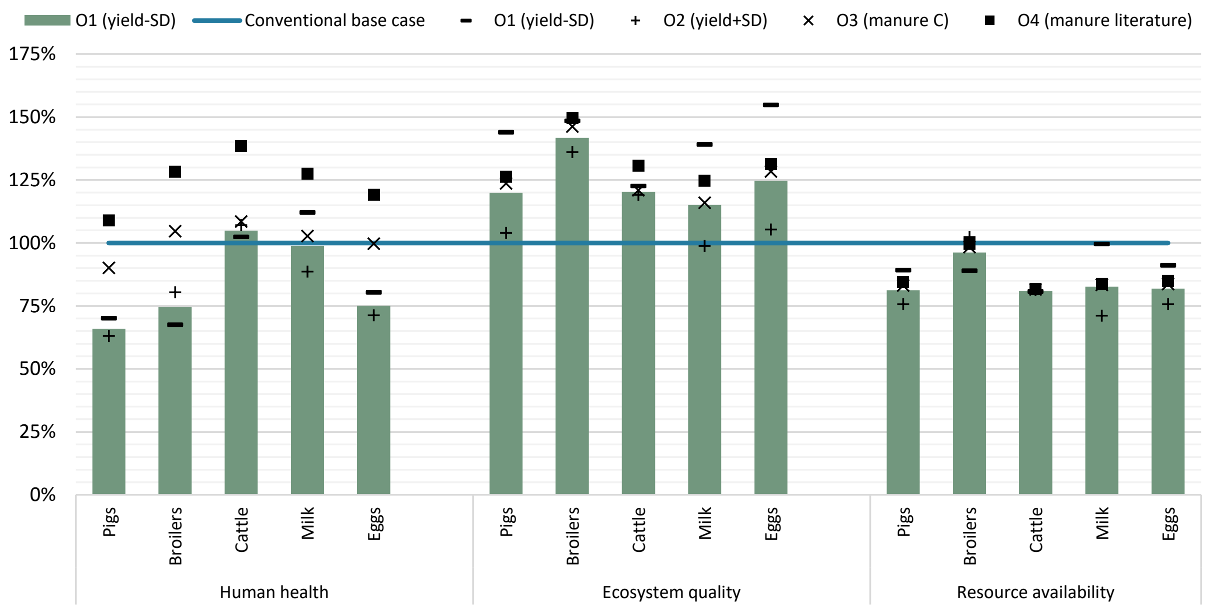


**Figure S1-7.** ReCiPe endpoints for animal-based foodstuff with organic scenarios (O) compared to the conventional base case (C) and influence of yield and manure.

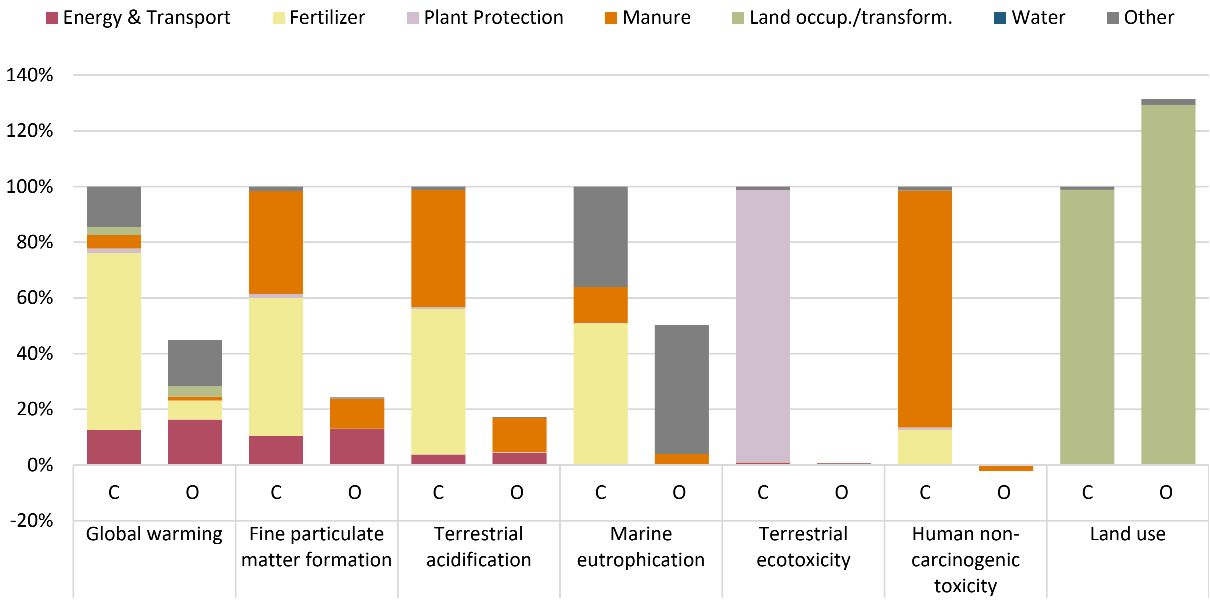


**Figure S1-8.** Process contributions for organic (O) and conventional (C) maize.

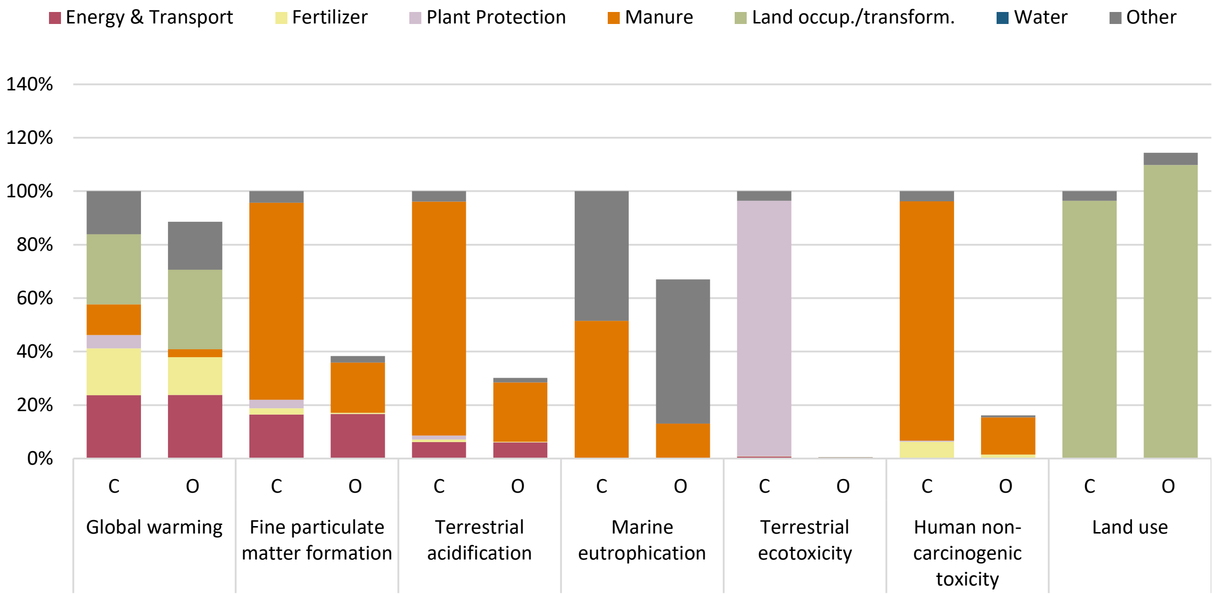


**Figure S1-9.** Process contributions for organic (O) and conventional (C) lupins.

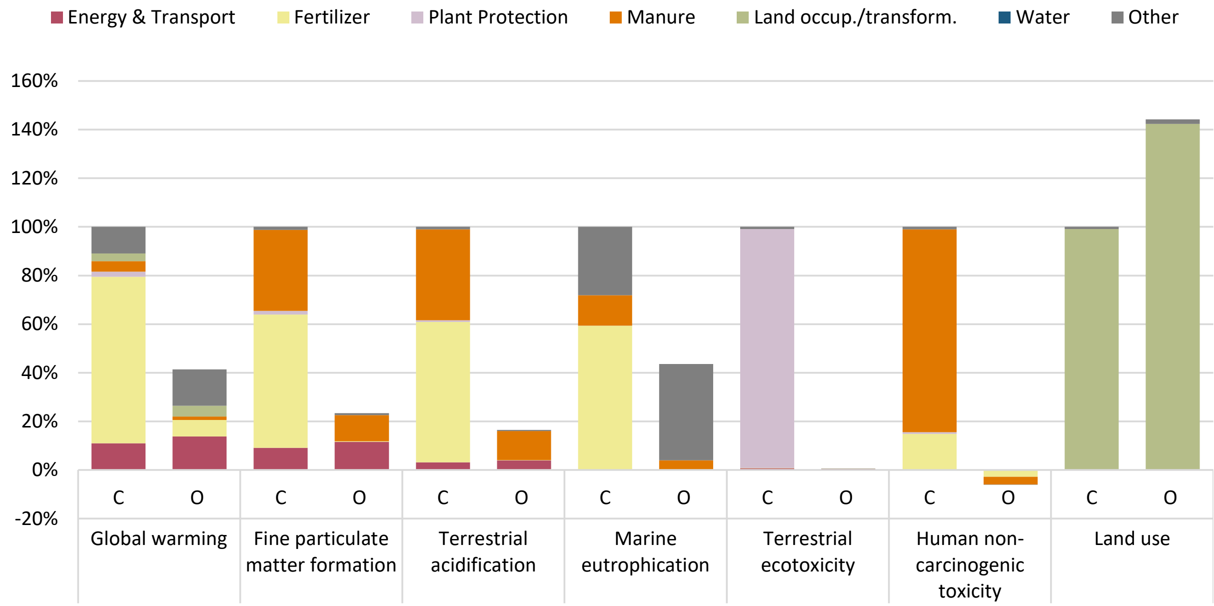


**Figure S1-10.** Process contributions for organic (O) and conventional (C) rapeseed.

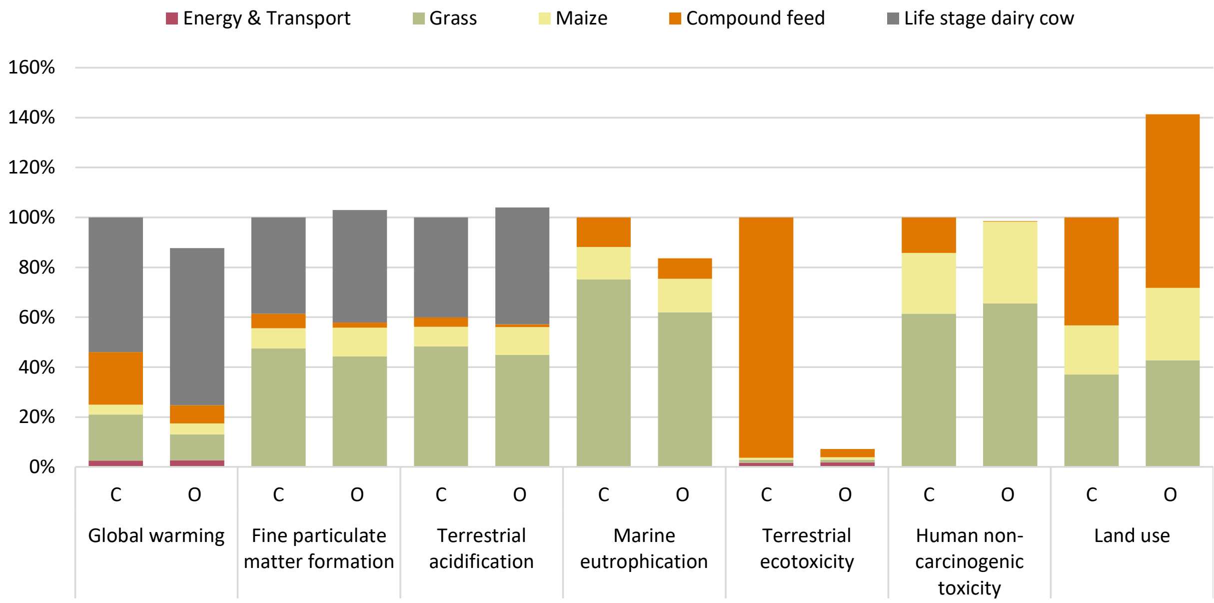


**Figure S1-11.** Process contributions for organic (O) and conventional (C) milk.

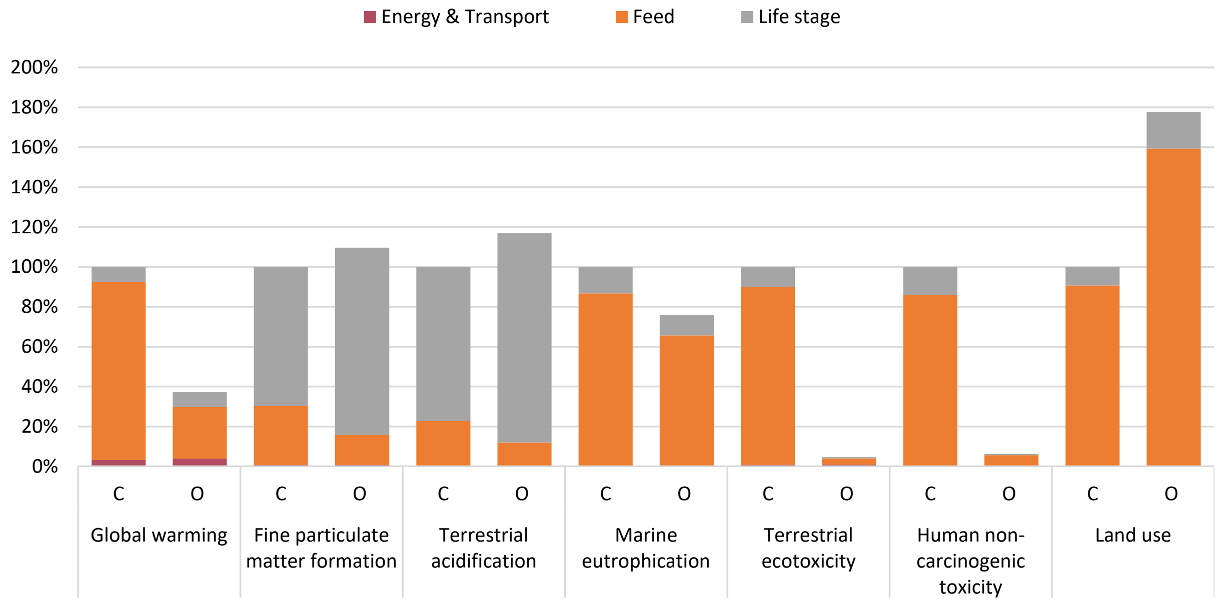


**Figure S1-12.** Process contributions for organic (O) and conventional (C) broilers.

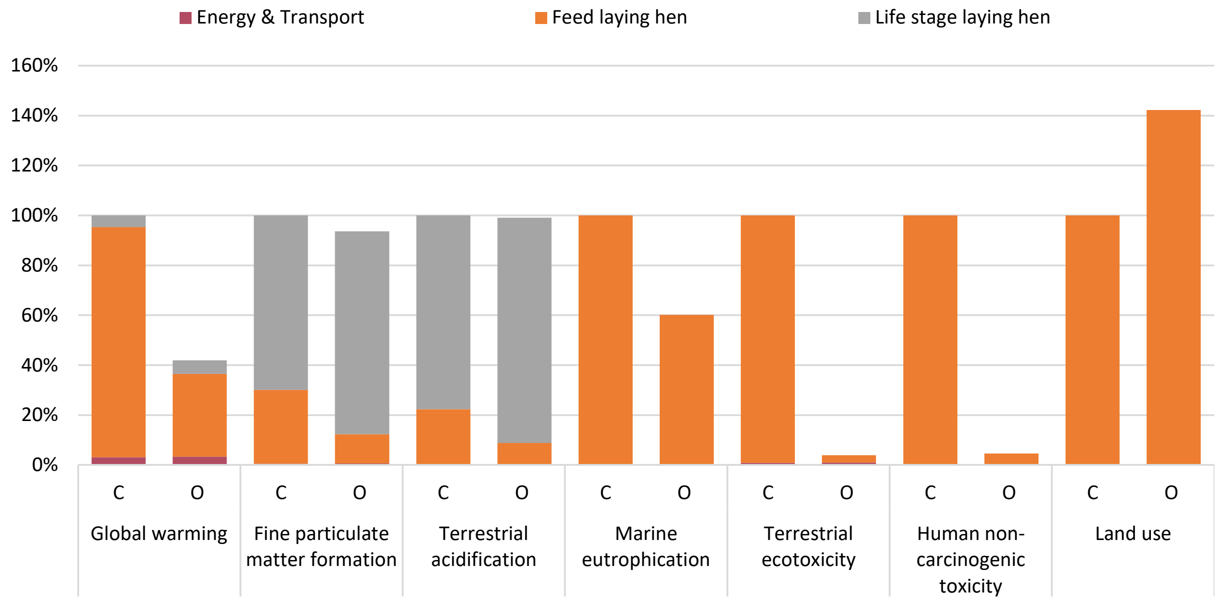


**Figure S1-13.** Process contributions for organic (O) and conventional (C) eggs.

## Composition of process contributions

**Table S1-3.** Process contributions for plant-based foodstuff (for full inventories, cf. Supporting Information S2, Appendix A9)

| | |
|---|---|
| **Energy & transport** | |
| C, O | - Transport of manure and other materials<br>- Energy (total fuel demand for on-field activities of arable crops)<br>- Electricity use for irrigating arable crops<br>- Basic infrastructure |
| **Fertilizer** | |
| C | - Fertilizers (di ammonium phosphate, ammonium sulfate, calcium ammonium nitrate, NPK compound, liquid urea-ammonium nitrate solution, urea, PK compound, single superphosphate, triple superphosphate, potassium chloride, potassium sulfate<br>- Emissions to air from fertilizers (carbon dioxide, dinitrogen monoxide, ammonia, nitrogen monoxide)<br>- Emissions to water from fertilizers (nitrate, phosphorus)<br>- Emissions to water from heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn)<br>- Emissions to soil from heavy metals (Cd, Cr, Cu, Hg; Ni, Pb, Zn) |
| O | - Lime fertilizer<br>- Emissions to air (Carbon dioxide, fossil)<br>- Emissions to water from heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn)<br>- Emissions to soil from heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn) |
| **Plant protection** | |
| C | - Insecticide, fungicide, herbicide and respective emissions |
| O | - None |
| **Manure** | |
| C, O | - Manure from pig and poultry<br>- Emissions to air (dinitrogen monoxide, ammonia)<br>- Emissions to water from heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn)<br>- Emissions to soil from heavy metals (Cd, Cr, Cu, Hg, Ni, Pb, Zn) |
| **Land occupation & transformation** | |
| C | - Land use based on estimated crop cycle (occupation) |
| O | - Land use change (transformation)<br>- Land use change impacts (carbon dioxide emissions to air) |
| **Water** | |
| C, O | - Irrigation water |
| **Other** | |
| C, O | - Amount of start material (seeds)<br>- Direct and indirect crop residues emissions (dinitrogen monoxide emissions to air, nitrate emissions to water) |

**Table S1-4.** Process contributions for animal-based foodstuff (for full inventories, cf. Supporting Information S2, Appendix A9)

| | |
|---|---|
| **Energy & transport** | |
| C, O | - Transport of feed from feed compound plant to farm<br>- Electricity<br>- Heat |
| **Grass** *(only applicable for beef cattle and milk)* | |
| C, O | - Grass<br>- Grass silage |
| **Compound feed** | |
| C, O | - Compound feed<br>- Wet by-product feed *(only applicable for milk)* |
| **Life stage** | |
| C, O | - Water for drinking<br>- Direct emissions during life stage |
| **Maize** *(only applicable for milk)* | |
| C, O | - Maize silage |

## Appendix A5 True Cost Accounting

**Table S1-5.** Cost factors

| Midpoint | unit | E [€] [1] | E1 [€] [2] | E2 [€] [3] | E3[€] [4] |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | 0.20 | 0.06 | 0.37 | 0.15 |
| Ozone depletion | kg CFC-11 eq | 30.40 | 22.10 | 45.70 | 31.80 |
| Ionizing radiation | kBq U235 eq | 0.05 | 0.03 | 0.06 | [5] |
| Photochemical oxidant formation | kg NMVOC | 1.15 | 0.84 | 1.84 | 2.22 |
| Particulate matter formation | kg PM10 eq | 39.20 | 28.00 | 60.40 | 31.64 [5] |
| Terrestrial acidification | kg $SO_2$ eq | 4.97 | 0.53 | 5.66 | 3.36 |
| Freshwater eutrophication | kg P eq | 1.86 | 0.25 | 2.11 | 304.00 |
| Marine eutrophication | kg N eq | 3.11 | 3.11 | 3.11 | 63.40 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 8.69 | 1.17 | 9.85 | 7.27 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 0.04 | 0.00 | 0.04 | 0.03 |
| Marine ecotoxicity | kg 1,4-DB eq | 0.01 | 0.00 | 0.01 | 0.01 |
| Human toxicity | kg 1,4-DB eq | 0.10 | 0.07 | 0.15 | 0.038 [6] |
| Land occupation | $m^2a$ | 0.0845 | 0.0255 | 0.6850 | 0.2390 [7] |
| Natural land transformation | $m^2$ | [9] | [9] | [9] | 0.0223 [7] |
| Metal depletion | kg Fe eq | [9] | [9] | [9] | 0.005 [8] |
| Fossil depletion | kg oil eq | [9] | [9] | [9] | 0.437 |
| Water depletion | $m^3$ | [9] | [9] | [9] | 1.27 |

[1] E: For global warming the price factor 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 is derived from the average values from the EPH, the German consumer price index of the Federal Statistical Office was used for price adjustment from 2015 to 2020 (Statistisches Bundesamt (Destatis), 2021). 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 is derived from Ricke et al. (2018), exchange rates of the European Central Bank were used to for currency conversion from USD to EUR (ECB, 2021). 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).
[5] The TPF documentation gives a cost factor of €46.20 per kg PM2.5 eq. To convert from PM2.5 to PM10, a characterization factor of 0.68 (de Bruyn et al., 2018) was used.
[6] The TPF documentation gives a cost factor of €54,800 per DALY. To convert from DALY to kg 1,4-DB eq, the ReCiPe 2008 midpoint-to-endpoint factor of $7{\cdot}10^{-7}$ was used.
[7] Grassland
[8] The TPF documentation gives a cost factor of €0.223 per kg Cu eq. To convert from Cu to Fe, the ReCiPe 2008 characterization factor of 42.7 kg Fe eq. per kg Cu eq. was used.
[9] No price factor available, which makes the monetized evaluation a conservative estimate.

After examination of the methodology used in EPH and consultation with the authors, we concluded to combine the cost factors of the EPH with the impacts assessed with ReCiPe 2008 (Goedkoop & Huijbregts, 2012) rather than 2016. This is since EPH's methodology is inherently linked with assumptions made in ReCiPe 2008 and would thus be inconsistent with 2016 and distort the results, especially in the case of ecotoxicity.

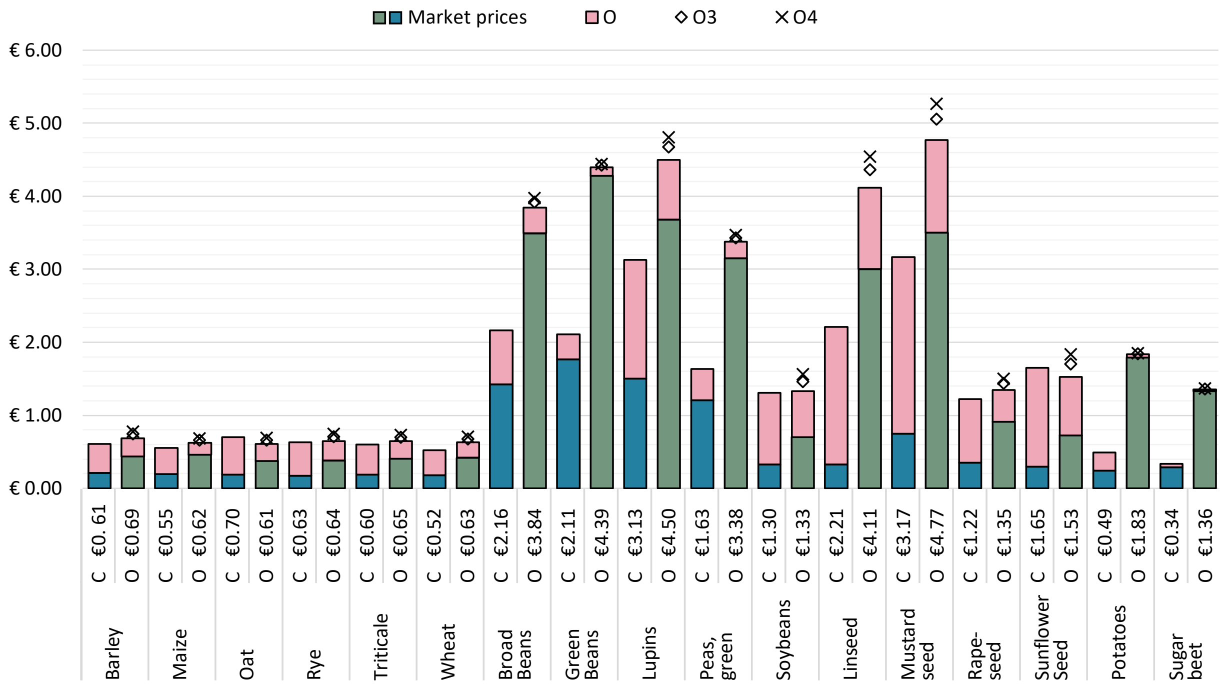


**Figure S1-14.** Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) plant-based products in scenarios O, O3, and O4 (i.e., with varying manure application). The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (E). All results shown per kg of product and for the year of 2020.

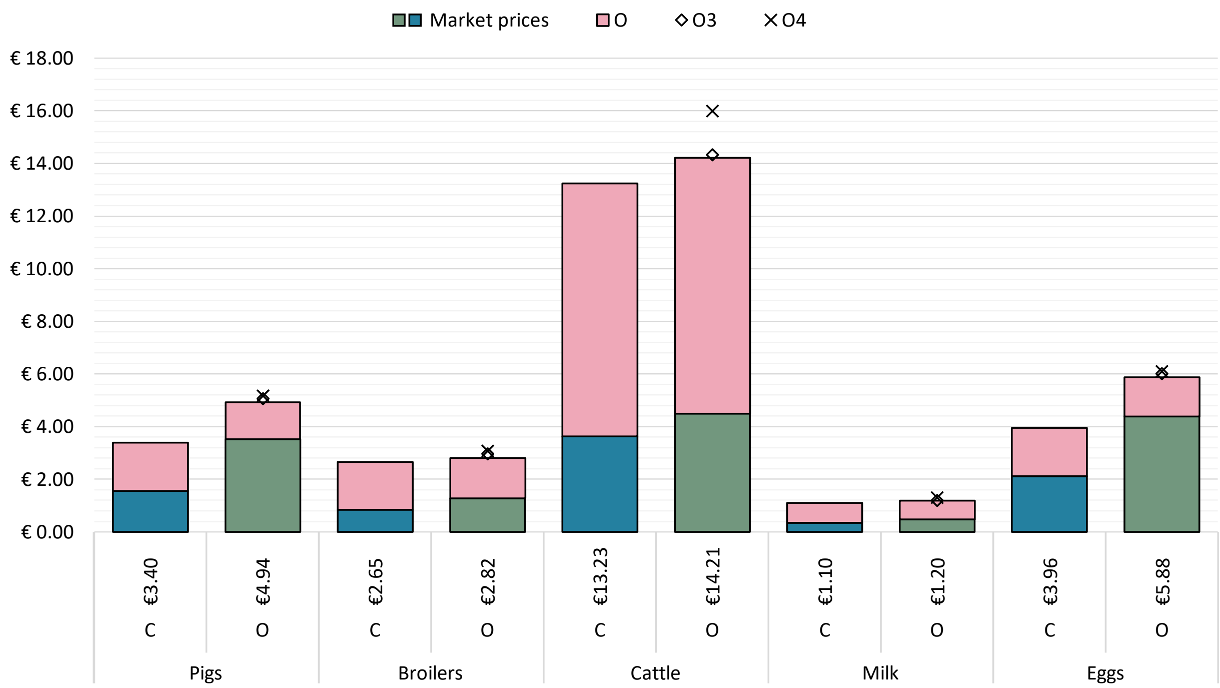


**Figure S1-15.** Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) animal-based products in scenarios O, O3, and O4 (i.e., with varying manure application). The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (E). All results shown per kg of product and for the year of 2020.

To account for the fact that in Germany, a significant amount of produced beef is a co-product of the dairy industry, we compare the distinct beef cattle (bulls; as presented in the manuscript) with dairy cows. This is presented in Figure S1-16. Additionally, we model a theoretical market mix. German production consists of 45.7% beef from beef cattle, 32.9% from dairy cows, and 21.4% from mainly calves (and others, e.g., oxen) (BIL 2021). Accounting for the fact that the results of the manuscript are presented per kilogram of live weight and for different slaughtering yields (56-57% for cows, 59-60% for bulls, <48% for calves; BLE 2010), when not including calves, the aforementioned distribution of beef production translates to a market mix of 56.9% and 43.1% for beef cattle and dairy cows (live weight), respectively.

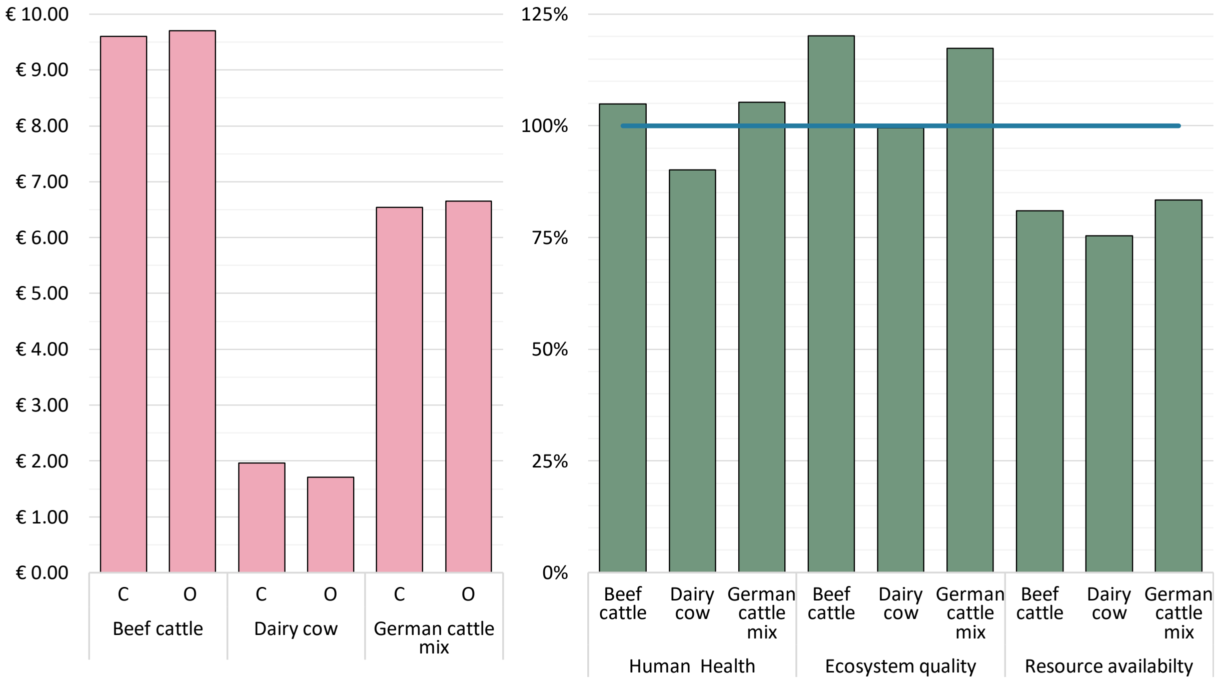


**Figure S1-16.** Externalities (conventional vs. organic; in €/kg) and LCIA endpoints (organic relative to conventional, 100% for each endpoint) of beef cattle, cows as co-products from milk production, and a German cattle mix.

**Table S1-6.** Overview of TCA results for the base case

| | MARKET PRICES | | EXTERNALITIES | | | | TRUE COSTS | | | PRICE INCREASE FROM MARKET PRICE TO TRUE COSTS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | MEAN | | | | | | | MEAN | |
| **Product** | **C** | **O** | **C** | **O** | **C** | **O** | **C** | **O** | **Unit** | **C** | **O** | **C** | **O** |
| Barley | 0.21 | 0.44 | 0.40 | 0.25 | 0.79 | 0.42 | 0.61 | 0.69 | €/kg | +188% | +57% | +210% | +41% |
| Maize | 0.19 | 0.46 | 0.36 | 0.16 | | | 0.55 | 0.62 | €/kg | +188% | +36% | | |
| Oat | 0.19 | 0.38 | 0.51 | 0.23 | | | 0.70 | 0.61 | €/kg | +277% | +61% | | |
| Rye | 0.17 | 0.38 | 0.46 | 0.27 | | | 0.63 | 0.64 | €/kg | +271% | +70% | | |
| Triticale | 0.19 | 0.41 | 0.41 | 0.24 | | | 0.60 | 0.65 | €/kg | +215% | +59% | | |
| Wheat | 0.18 | 0.42 | 0.34 | 0.22 | | | 0.52 | 0.63 | €/kg | +185% | +52% | | |
| Broad beans | 1.42 | 3.49 | 0.74 | 0.35 | | | 2.16 | 3.84 | €/kg | +52% | +10% | | |
| Green beans | 1.77 | 4.28 | 0.34 | 0.11 | | | 2.11 | 4.39 | €/kg | +19% | +3% | | |
| Lupins | 1.50 | 3.68 | 1.63 | 0.82 | | | 3.13 | 4.50 | €/kg | +109% | +22% | | |
| Peas, green | 1.21 | 3.15 | 0.42 | 0.23 | | | 1.63 | 3.38 | €/kg | +35% | +7% | | |
| Soybeans | 0.32 | 0.70 | 0.98 | 0.63 | | | 1.30 | 1.33 | €/kg | +303% | +89% | | |
| Linseed | 0.33 | 3.00 | 1.88 | 1.11 | | | 2.21 | 4.11 | €/kg | +570% | +37% | | |
| Mustard seed | 0.74 | 3.50 | 2.43 | 1.27 | | | 3.17 | 4.77 | €/kg | +326% | +36% | | |
| Rapeseed | 0.35 | 0.91 | 0.87 | 0.43 | | | 1.22 | 1.35 | €/kg | +246% | +47% | | |
| Sunflower seed | 0.30 | 0.73 | 1.36 | 0.80 | | | 1.65 | 1.53 | €/kg | +457% | +110% | | |
| Potatoes | 0.24 | 1.79 | 0.26 | 0.04 | | | 0.49 | 1.83 | €/kg | +107% | +2% | | |
| Sugar beet | 0.29 | 1.33 | 0.05 | 0.03 | | | 0.34 | 1.36 | €/kg | +16% | +2% | | |
| Pork | 1.55 | 3.53 | 1.85 | 1.41 | 4.42 | 4.22 | 3.40 | 4.94 | €/kg | +119% | +40% | +200% | +125% |
| Poultry | 0.84 | 1.28 | 1.81 | 1.54 | | | 2.65 | 2.82 | €/kg | +216% | +120% | | |
| Beef | 3.63 | 4.50 | 9.60 | 9.71 | | | 13.23 | 14.21 | €/kg | +265% | +216% | | |
| Milk | 0.35 | 0.48 | 0.75 | 0.72 | 1.29 | 1.10 | 1.10 | 1.20 | €/kg | +212% | +149% | +149% | +91% |
| Eggs | 2.12 | 4.39 | 1.84 | 1.49 | | | 3.96 | 5.88 | €/kg | +87% | +34% | | |

Table S1-6 shows the overall TCA results for the conventional and organic base case monetized with EPH (average) values. The average externalities for all conventional food groups (plant-based, animal, and animal-based) exceed those of their organic counterparts. Yet, true costs (sum of market price and externalities) for all organic products (except for oat and sunflower seeds) are still higher than those of conventional products in most cases. This underlines that current pricing levels of foodstuff are inadequate in terms of the "polluter-pays" principle. Higher environmental pressure put on the environment by conventional production is not accounted for in the current market prices. By implementing TCA, price levels of organic and conventional production converge, but the internalized externalities cannot close the price gap. Additionally, the results reveal a major impact of dietary behavior. Meat and dairy-based foodstuff lead to considerably higher externalities than plant-based foodstuff, regardless of the production method. This notion is understandable, as process chains of livestock are complex and require more resources and consequentially more emissions than plant production. Therefore, consumers' dietary behavior should transition towards a more plant-focused diet, which could be induced by internalizing external costs into market prices that would disproportionately penalize animal-based products − contributing to the sustainable development goals and also yielding health benefits for consumers.

## Appendix A6 Sensitivity Analysis

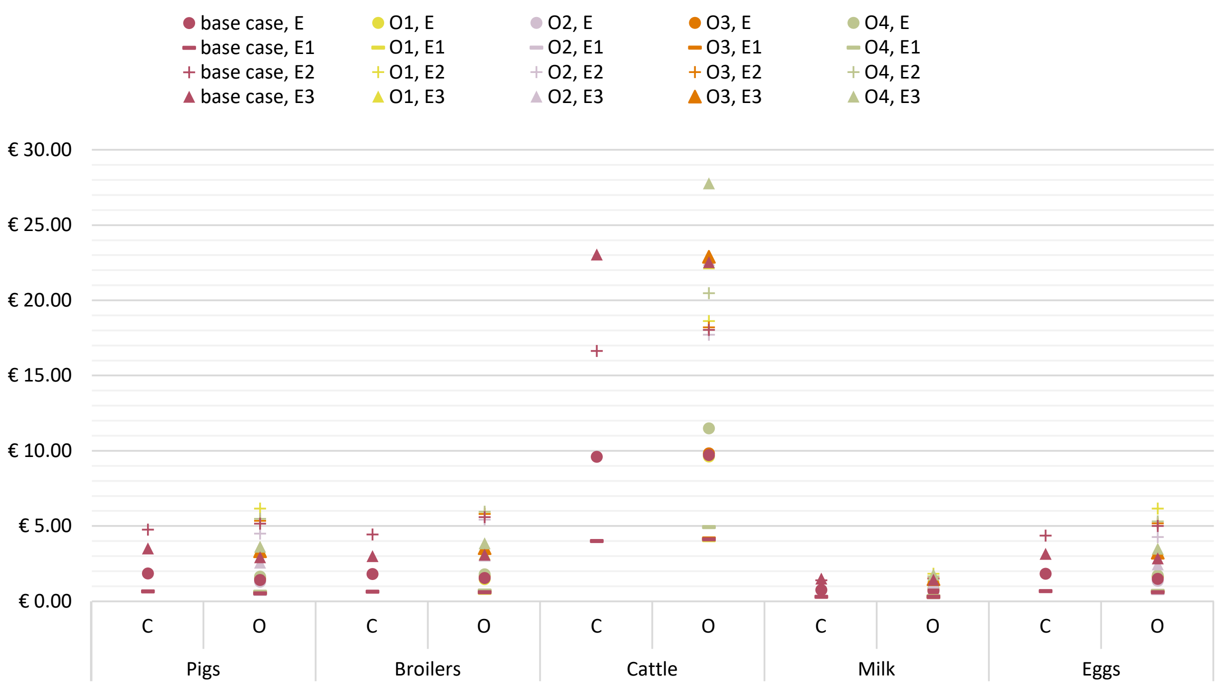


**Figure S1-17.** Sensitivity analysis of externalities for organic (O) and conventional (C) animal-based products. For explanation of abbreviations to pricing methods and production scenarios see table 1.

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