Towards True Cost Accounting of Agricultural Food Products

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List of scientific contributions

The following published, accepted, or submitted scientific contributions are presented within this doctoral dissertation. Corresponding Authors are marked with * next to their name.

Contribution A

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Contribution B

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Contribution C

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Contribution D

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Contribution E

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INTRODUCTION

Agricultural products feed the world and their production secures the livelihood of more than a quarter of the global population (ILO 2018). In other words, agriculture sustains human life on earth. But today's agricultural production is far from sustainable for the planet and its people. Therefore, agricultural transformation is paramount to secure food and environmental safety globally. This dissertation explores one auspicious measure aiming at sustainable transformation of agri-food systems: True Cost Accounting of agricultural food products.

In this section, I will first discuss certain issues with current global agricultural practice – like its emission of pollutants or extensive use of resources – and explore selected solutions – like alternative farming practices or dietary transitions. I then introduce the concept of True Cost Accounting (TCA), a method that integrates both issues and solutions into one measure to achieve a more sustainable agri-food system. I will also explain, how this dissertation advances the understanding of TCA.

The Intergovernmental Panel on Climate Change (IPCC) finds agriculture, forestry and other land use (AFOLU) responsible for just under one quarter, or 13 billion tons, of global greenhouse gas (GHG) emissions (Smith et al. 2015; IPCC 2022). In Germany, the share of GHG emissions from agriculture compared to the country's total output is likewise considerable: in 2021 about 7% of German GHG emissions are borne from agriculture alone (including production and storage of energy crops but excluding forestry and other land use). Of this, about 66% are attributable to livestock (UBA 2021), and about 53% are related to cattle alone (Rösemann et al. 2021). In 2020 the total AFOLU in Germany causes 103.6 million tons of GHG, amounting to 14% of the country's total output (UBA 2020).

Agriculture is also the largest freshwater consumer globally: about 69% of freshwater is withdrawn for food production. Climatic differences change this figure regionally, with the agricultural sector using up to 90% of freshwater in arid regions. This great share of water use globally also underlines the vulnerability of the food sector to water shortages and scarcity in the light of climatic change, especially in countries of the periphery[1] in sub-Saharan Africa, Asia or Latin America. (UN 2018)

Agriculture is known as the primary driver of deforestation (FAO 2020). Forests, which cover almost one third of the planet's land mass, provide important ecological benefits like GHG mitigation or freshwater supply (FAO 2020). They are also of economic importance providing timber and non-wood forest products, but also securing livelihoods of many people (FAO 2014) including the 60 million indigenous people living in forests (Shvidenko et al. 2005). Between 1990 and 2015 about 129 million hectare (ha) of forest was lost and due to land use change (LUC) – e.g., forest to cropland for agricultural production – their carbon stocks (carbon stored in organic matter and therefore acting as carbon sinks) have decreased drastically (FAO 2016). While the yearly rate of deforestation has dropped over the turn of the millennium, it is still ongoing practice at rates endangering a majority of floral and faunal species (FAO 2020). This not only is a threat to biodiversity but is likewise benefitting the development of pandemics, such as COVID-19 (Gibb et al. 2020; Tollefson 2020).

To enhance plant growth and therefore agricultural productivity, farmers use fertilizers for sufficient nutrient supply to plants. For this, human activities have been altering the global nitrogen cycle significantly (Galloway et al. 2008): at the beginning of the 20th century, the Haber-Bosch process allowed for ammonia (NH_3) to be produced with energy and N_2 from the atmosphere. This cheap source of soil nutrients is regarded responsible for an immense increase in crop yield and as consequently supporting an ever growing population throughout the last century (Erisman et al. 2008). However, Sutton et al. (2011a) describe in the *European Nitrogen Assessment* how about 50% of agriculturally used reactive nitrogen in Europe is eventually lost

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[11] Countries of the periphery, semi-periphery or core are defined and structured under the World Systems Theory, in which historical developments and dependencies between countries that shape today's systems (be they economic or societal) are considered: core countries hold power over peripheral societies; this structure is upheld as core states govern and can consequentially maintain an imbalanced distribution of resources and therefore power. (Martínez-Vela 2001)
In this work, I will use the term *core countries* (or similar) for conventionally known "developed" countries and the term *countries of the periphery* (or similar) for "developing" countries. Within constituent Contributions A to E, other terms may be used according to the publishing journals' guidelines.

to the environment as emissions to soil, air, and water and that agriculture is the main source of anthropogenic reactive nitrogen emissions (except for nitrous oxides, where fossil-fuel burning holds the largest share). Reactive nitrogen pollution causes manifold disturbances in natural systems, like algal bloom or particulate matter production, which endangers both the health of ecosystems and humans (Sutton et al. 2011b). The planet's boundary for reactive nitrogen emissions is considered exceeded to an alarming degree (Steffen et al. 2015). Global nutrient injustice prevails, however: while core countries' nitrogen balances are net positive – in Germany, for example, on average 80 kg of reactive nitrogen is emitted for every agriculturally used ha (BMEL 2021) – countries of the periphery suffer from a lack of nutritious soils and therefore struggle to feed their population (Sanchez and Swaminathan 2005; Galloway et al. 2008). Not only does fertilizer use drastically enhance reactive nitrogen in the atmosphere, the production of fertilizer is also an energy intensive process and is reported as the biggest consumer of energy in the agricultural sector of the EU (Paris et al. 2022).

Even if it is common knowledge how today's agricultural systems insufficiently pursue ecological sustainability objectives, dietary guidelines are only very slowly aligning with environmental knowledge (Blackstone et al. 2018; Tuomisto 2018). Aside striving for healthful and holistic diets, generally feeding the world remains a challenge yet to be accomplished by global agricultural systems (Godfray et al. 2010): 9.9% of the global population are undernourished in 2020 (rising from previous years due to the COVID-19 pandemic); over 2.3 billion people are facing food insecurity and healthy diets are financially or logistically unreachable for 3 billion people – especially the poor in peripheral countries (FAO 2021). Sociopolitical instability and climatic events – which have greater effects on countries of the periphery (Bathiany et al. 2018) and their agricultural productivity (McMichael et al. 2007; Karki and Gurung 2012; Anderson et al. 2020) – further reinforce food insecurity and consequently global hunger: external shocks impact food security of poor households to a greater degree since one of the households' main expense is oftentimes the cost for food (FAO 2018).

These issues of environmental and social concern are known and well researched. Yet, realizing agricultural transformation towards more sustainability and resilience in order to contain further natural disruptions and to react to current and future changes of the natural world seems insufficient (IAASTD 2009; IPCC 2022). As Gemmill-Herren et al. (2021) state:

“Understanding our planetary boundaries is necessary to guide change but not sufficient to effect action.”.

However, action is indeed urged for agricultural production and consumption to transform sustainably. One route of action oftentimes proposed is decreasing the intensity of prevailing conventional – or industrial – agriculture. A promising measure is greater adoption of practices that are oriented towards natural processes rather than only economic efficiency. There are farming approaches that aim at exactly this: Agroecology, for example, applies ecological principles and aims at sustainable resource and ecosystem service use (HLPE 2019). Practices anchored in food-related agroecology are, amongst others, the diversification of crops, or effort on soil improvements (Bezner Kerr et al. 2021). Diversified farming, as another example, uses diversification along ecological (e.g., diverse crop or livestock species, intercropping, etc.), spatial (including measures on field like composting), and temporal (e.g., crop rotations) frames to reap benefits of the cultivated land and its provided ecosystem services (Kremen and Miles 2012). Besides ecological benefits, evidence shows that diversified farming is also competitive to other practices from an economic point of view, depending on the specific system and way in which diversified farming is applied (Sanchez Bogado et al. 2022).

Organic farming is another approach that is considered sustainable. It is also, contrary to agroecology and diversified farming, rooted in legislative regulations (Rigby and Cáceres 2001) since the late 1980s with now about 100 countries setting national standards for organic production (Seufert et al. 2017). The International Federation of Organic Agriculture Movements (IFOAM) describes how organic agriculture “relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects.” (IFOAM 2008). These organic practices are potentially beneficial for the environment (Reganold and Wachter 2016; Seufert and Ramankutty 2017) especially for an area-based valuation (Meemken and Qaim 2018). Due to ever rising demand of organic produce globally, the organically cultivated agricultural land has risen from 1.1 million ha in 1999 to 71.5 million ha in 2018 while the market has increased from sales of 15.1 billion euros in 2000 to 96.7 billion euros in 2018 (FiBL and IFOAM 2020). A further expansion of the organic sector is anchored in national sustainability strategies. For example, the German Sustainable Development Strategy aims at 30% organically managed agricultural area by 2030 (Die Bundesregierung 2021), the European Farm to Fork Strategy at 25% (European Commission 2020). Even the UN describes organic agriculture as part of the solution to reach the Sustainable Development Goals

(SDG) (Schaetzen 2019). Nevertheless, critics argue that the inferior productivity of organic compared to conventional land – yield gaps are reported at around 20% on average (Ponti et al. 2012; Seufert et al. 2012; Ponisio et al. 2015) – counteract the alleged environmental or social benefits as land use would increase (Connor and Mínguez 2012; Muller et al. 2017). Others argue as well that food costs would increase, putting ever more pressure on already marginalized communities (Meemken and Qaim 2018).

Undoubtedly, further endeavors to transform agricultural production sustainably are urgently necessary. Nevertheless, transforming production processes is not the only lever considered to bring about agricultural sustainability. A changing consumption of agricultural products, or sustainable dietary transformation, is also known to hold major potential for reducing pressure on environment and society (Poore and Nemecek 2018). One such route is the consumption of products that are primarily regionally sourced. There is potential for environmental benefits, for example through saving long transportation routes (Smith et al. 2005). While food miles are indeed being spared, studies nevertheless describe how a mere minority of food related GHG emissions are associated with the transportation process (Weber and Matthews 2008) and how close proximity between production and consumption site alone is not a sufficient indicator for environmental favorability (Edwards-Jones et al. 2008; Coelho et al. 2018) and can even lead to environmental trade-offs (van Passel 2013).

Another arguably more promising measure on the consumption side of sustainable agricultural transformation is decreasing the reliance on livestock for food supply. Reducing animal products from diets is linked with a reduction of greenhouse gas emissions (especially methane and nitrous oxide) (Eshel and Martin 2006; McMichael et al. 2007; Stehfest et al. 2009; Nijdam et al. 2012; Tilman and Clark 2014; Westhoek et al. 2014; Poore and Nemecek 2018; Pieper et al. 2020), non-CO_2 emissions (Popp et al. 2010; Westhoek et al. 2014; Poore and Nemecek 2018), and the use of agricultural area (Stehfest et al. 2009; Nijdam et al. 2012; Poore and Nemecek 2018). An increase of energy consumption (Eshel and Martin 2006; Marlow et al. 2009), water, fertilizer and pesticide use (Marlow et al. 2009) is also associated with higher shares of animal-based products in the diet.

As described, a sustainable transformation of the agricultural sector – on both the production and consumption side – must proceed with greater determination than heretofore; not least to achieve global sustainability objectives such as the UNs 17 SDGs for global sustainability in natural, economic, and societal systems (UN 2016). These SDGs include goals directly or indirectly linked to agricultural production (e.g., SDG 2: “Zero hunger”, through equitable agricultural production or SDG 5: “Gender equality”, since women are more likely to be facing food insecurity than men, sustainable food systems hold potential for gender equality) (Djekic et al. 2021; UN 2021). However, interdependencies and tradeoffs between the different goals complicate sustainable development (Nilsson et al. 2016). For example, increasing productivity of agricultural systems to reach zero hunger would benefit SDG 2 (“Zero hunger”) but is likely to increase the strain on the environment through highly intensive production and therefore counteracts at least SDG 12 (“Responsible consumption and production”), 13 (“Climate action”), 14 (“Life below water”), 15 (“Life on land”), to a certain extent. Defining measures of progress towards achieving the goals is imperative for determining to which extent economic activities, be they agricultural or not, contribute or impede on global sustainability endeavors (Vörösmarty et al. 2018; Buonocore et al. 2019). In SDG 17 (“Partnerships for the goals”), which is described as the perquisite for the achievement of all other SDGs (UN 2016), such measures that draw on the economic language of sustainability are explicitly stipulated: under “Data, monitoring and accountability”, the last sub-target 17.19 aims at “measurements of progress on sustainable development that complement gross domestic product”, with one indicator being the availability of a dollar value of all resources (UN 2022).

One such measure is the concept of True Cost Accounting (TCA) (El-Hage Scialabba et al. 2021). TCA sets out to visualize negative or positive impact contributed along the value chain of a commodity that is not considered by producers, consumers, or policy makers (TEEB 2018; Baker et al. 2020; Castilleja 2021). With TCA, this impact is either reported qualitatively, quantitatively, or in monetary terms. The latter describes the “hidden cost” (or “hidden benefit” with a surplus of positive impact) of a production system and makes visible the market distortions due to uninternalized externalities (Baker et al. 2020). TCA is a tool that can be used regardless of the industry a product belongs to. It can also be used to describe the sustainability, or lack thereof, of production practices or enterprises (True Cost Initiative 2022). Fields of application of TCA are diverse. Investment consultants engage with principles of TCA to prepare businesses for possible mandatory environmental accountability (like subsidy removal or a spread of the carbon pricing system) (KPMG 2012). In the food context, TCA is used for several purposes (Castilleja 2021): public welfare oriented organizations use TCA for increasing awareness and transparency of agricultural externalities for better informed decisions of consumers, producers, and policy-makers (TMG and WWF 2019; True Cost Initiative 2022); food companies engage in TCA to make negative impacts along their value chain visible, find potential of minimizing this impact (EOSTA 2017), or use it to engage with consumers through informational campaigning of unsustainable effects of food (Michalke et al. 2020); farmers use TCA to account and communicate the total benefits – through services to the soil, or animals, for example – of their specific production practices (Wollesen et al. 2021).

Findings of previously conducted TCA in the food context point overtly towards the inadequate incorporation of the previously described ecological and societal damage within agri-food networks' pricing mechanisms. In "The True Cost and True Price of Food", a publication of the United Nations Food Systems summit (Hendriks et al. 2021), authors estimate the global food system's negative externalities at $19.8 trillion annually, including approximate costs of $7 trillion to the environment, $11 trillion to human life, and $1 trillion to the economy. Other results present not as drastic, yet figures are still in the red: the Food and Land use Coalition finds hidden annual costs of $12 trillion (costs of $6.6 trillion to health, $3.1 trillion to the environment, $2.1 to the economy), which is compared to a market value of $10 trillion (Pharo et al. 2019). Similarly, the Sustainable Food Trust establishes that for every pound spent for food in the UK, another pound is spent in environmental or health-related costs (Fitzpatrick et al. 2019). In the context of the US, however, the Rockefeller Foundation finds that the external costs of US food systems even triple their current expenditure (The Rockefeller Foundation 2021). Such drastic market distortions, be they conveyed by a disparity ratio of 1:1, 1:2, or even 1:3, call for more insight in the evaluation of true food prices.

Therefore, TCA, as a rather novel strand of research within the grand field of sustainability science in the food context, will be addressed within this work from different perspectives. This work first sets out to find if economic, ecological, or social incentives drive consumers towards or against dietary decisions (Contribution A). It then develops a framework of TCA for food to describe economically conveyed incentives that are tied to ecological and social indicators within the food market (Contribution B). The framework is subsequently enhanced and broadened to include a deeper understanding and broader field of indicators for more holistic TCA calculations (Contributions C and D). Lastly, based on these calculations, TCA of food is implemented in a factual use case as the framework and calculations are deployed for commodities of a German supermarket chain; then consumer, as well as expert feedback is used for the discussion on socially responsible campaigning and policy change (Contribution E).

During this scientific progression, the following research questions will be answered:

RQ1: Which factors of sustainability influence dietary behavior? (Contribution A)

RQ2: What is the framework of TCA in the context of agricultural goods and how are market prices of food affected when adding external costs of production?

RQ2.1: How can climate costs of different foods and production practices be calculated and how do they relate to current market prices? (Contribution B)

RQ2.2: What is the impact of global land use change from food consumption and what is its monetary damage? (Contribution C)

RQ2.3: How does an internalization of monetized environmental impacts for different food products and farming scenarios influence market prices? (Contribution D)

RQ3: How does informational campaigning of TCA affect customers' perspective on dietary decisions and what are potentials and burdens of socially responsible TCA implementation? (Contribution E)

For a better understanding of the herein employed methods, in the following I will first explore the interdisciplinary methodological background of this work. Each academic contribution will then be highlighted to convey the scientific proceedings of this work. Lastly, I draw conclusions from all contributions and the general impact of these conclusions in direction of political, societal, and scientific stakeholders.

2

METHODOLOGICAL BACKGROUND

Since TCA lies at the intersection of natural, economic, and social sciences, the overarching challenge of this work is the combination of all mentioned disciplines. I will first explore the methodological background of Life Cycle Assessment (LCA) in subsection 2.1, which is needed for describing, analyzing, and calculating the ecological indicators of TCA. LCA is subsequently combined with different costing methods, which will be preparatorily discussed under subsection 2.2.

2.1 Life Cycle Assessment (LCA)

LCA is used to record and analyze environmental burdens of a product or service. These burdens can be assessed along the entire life cycle, which encompasses all life cycle stages from the input of raw materials to the removal of waste (Klöpfer 1997). LCA is used to answer questions on the favorability of products based on their environmental performance (van der Werf et al. 2020) and is primarily a decision-making tool for process and design optimization, or eco-efficiency (Pryshlakivsky and Searcy 2021). The method of LCA has been standardized within the norm ISO 14040 and 14044 (ISO 2006a, 2006b).

According to the ISO standard, LCA follows four steps: (1) goal and scope definition, (2) Life Cycle Inventory, (3) Life Cycle Impact Assessment, and (4) interpretation of results. In step (1), the system boundaries are defined, which describe the scope of the observation, meaning what products are assessed and under what conditions. It is also considered, towards what audience the LCA will be targeted respectively what goal is being pursued with the assessment. This requires the definition of assumptions (i.a., if products are compared to one another, or what life cycle stages are included) and a functional unit (i.e., the unit of the product or service based on which further steps are performed) (Silva 2021). In step (2), the Life Cycle Inventory

(LCI), the functional unit of the product or service are modelled as inputs and outputs of sub-processes or material and energy flows. Sub-processes, as well, are either comprised of inputs and outputs of sub-processes or material and energy flows. Through this iterative modelling, all material and energy flows are eventually recorded along the assessed life stages of the product or service and can be cumulated (Rodrigues et al. 2021). In step (3), the Life Cycle Impact Assessment (LCIA), the environmental impacts of all material and energy flows are quantified. This is done with existing LCIA methods that use characterization factors translating all input or outflows to environmental impact, which is divided into different impact categories (midpoints). The environmental impact presented within the midpoints can then be aggregated to damage on areas of protection (endpoints). Midpoints, or impact categories, are (non-exhaustive list), for example, global warming potential, marine ecotoxicity, or mineral resource scarcity; endpoints, or areas of protection, are human health, ecosystems, and resource availability[2] (Huijbregts et al. 2017; Pavan and Mendes 2021). In step (4), results of the first three steps are interpreted before the background of the previously defined goal and scope of the LCA. An iterative evaluation, communication, and adaptation of estimates, assumptions, and methodological decisions occurring throughout the previous LCA stages is likewise part of the interpretation as is an observation of intermediate and final results. The interpretation is used to identify environmental hotspots (e.g., stages along the process chain or midpoints of remarkable values), as well as to evaluate the assessment according to its completeness, sensitivity, and consistency. With a careful interpretation, considering all aforementioned influencing factors, a provision of stakeholder-oriented conclusions, limitations, and recommendations is possible (Saade et al. 2021).

[2] This is based on the midpoint and endpoint definition of the LCIA method ReCiPe (Huijbregts et al. 2017). There are several LCIA methods, which use different characterization factors, time horizons, and mid- or endpoints, all of which are not precisely predefined by ISO 14040 and 14044. Other LCIA methods are, for example, CML2001, Eco-Indicator 99, or Ecological Footprint.

2.2 Environmental costing

Calculating environmental externalities can be achieved when monetarily valuating LCA results (Amadei et al. 2021). Life Cycle Costing (LCC), as part of a full Life Cycle Sustainability Assessment (LCSA), aims at recording all costs associated with a product or service throughout its full life cycle (Swarr et al. 2011). Whilst is has been discussed to include environmental externalities based on LCA results into the LCC (Steen 2005), as of now, only those environmental costs that are accounted for in the balance of at least one actor along the value chain are included in LCC (Swarr et al. 2011) and which are therefore no externality. Such costs could be, for example, costs for emission trading or costs of decarbonizing one's energy use.

Environmental costs that are not part of a physical costing balance are therefore an externality and the research subject of this work. They describe the loss of welfare to society through the burden of one unit of environmental impact (Bruyn et al. 2018). Thus, measures of social and biophysical impacts – or goods for which currently no market exists – are converted into monetary units, which hence enables comparison between different impact categories (Pizzol et al. 2015). There are different costing types, a combination of which is seen as a sensible approach to adequately depict the economic damage of environmental impact (Pizzol et al. 2015; Amadei et al. 2021; Galgani et al. 2021). Their individual use also depends on the policy objective the assessment is targeted at (Oberpriller et al. 2021). The two main methods of costing are the abatement cost approach and the damage cost approach:

Abatement costs, or mitigation costs, describe the costs occurring through the reduction or prevention of one additional unit of emission (Guerriero 2020; Amadei et al. 2021). Reduction may be achieved through treatment (i.e., removing pollution after emission, e.g., with air filters), recycling (i.e., processing waste or emission for another use, e.g., using CO_2 for the production of synthetic hydrocarbon fuels like synthetic natural gas (Hepburn et al. 2019)), disposal (i.e., displacing emission or waste from production, e.g., binding CO_2 in cement (Hepburn et al. 2019)), or prevention (i.e., a method or process reducing the emission before its generation, e.g., using renewable energy sources instead of fossil energy) (Guerriero 2020). The marginal abatement cost method has been widely used for supporting decision-making in climate change related issues (Huang et al. 2016), since it can described as the cost to reach a certain mitigation target or the cost of a certain mitigation measure (Oberpriller et al. 2021). It is, however, subject to large uncertainties due to assumptions and vague predictability of future circumstances (e.g., uncertain technological advances) (Oberpriller et al. 2021).

Damage costs describe the costs of damage through environmental impact. This damage can occur due to emission or pollution and its following impact (e.g., emission of GHG leads to climate change, which in turn leads to large scale weather events subsequentially damaging communities), or other changes in natural capital (e.g., sealing of soil for space of a production facility and subsequential loss of biodiversity) (Amadei et al. 2021). Both restoration and compensation costs can fall into this category: restoration costs are incurred to restore a system to its initial position (or a defined target position) through defined restoration measures (e.g., afforestation after land use change) (Ott et al. 2006); compensation costs are incurred to reimburse society for carrying the economic or non-economic burden of the environmental impact caused by production or consumption processes (Galgani et al. 2021). The damage cost approach can be used to underpin effects of political inaction, as it shows the economic consequences of failing to achieve certain sustainability targets. Further, it is the consequential costing measure of the polluter pays principle (Oberpriller et al. 2021).

There are several approaches that use one of the two, or a combination of both costing methods to monetarily valuate results of LCA (i.a., Bruyn et al. 2018, Matthey and Bünger 2019, Galgani et al. 2021). To achieve this valuation, midpoints are weighted with the according environmental cost and therefore an aggregation of all environmental impact to one single monetary value is achieved (Bruyn et al. 2018). The costs of endpoints could also be evaluated but play no further role in the calculations presented herein, since common methods of costing use midpoint valuation.

3

CONSTITUENT ELEMENTS OF THIS DISSERTATION

The dissertation's main work comprises five contributions, which highlight the overarching theme of TCA from different perspectives and with different methods. This enables a profound understanding of the necessity for TCA, its methodological approach, and the potentials and obstacles of its implementation. Contribution A explores driving factors of sustainability and their likeliness to effect dietary transformation. After finding economic incentives to mostly drive consumers' dietary decisions, Contributions B, C and D explore a framework of TCA to calculate environmental externalities of different foodstuff. This results in a depiction of "true" market prices and hence delivers financial incentives for sustainable food consumption. Contribution E investigates an implementation of foodstuff TCA in business practice – and therefore financial incentives – and also explores chances and obstacles of a broad introduction of TCA measures in agri-food systems.

In the following, I will give a brief overview over the research questions addressed and the methods used in each contribution. Further, main results will be discussed, and lastly core conclusions will be shortly presented.

3.1 Influencing factors for sustainable dietary transformation – A case study of German food consumption

To find how to foster sustainable dietary transformation best, Contribution A focuses on the influence of sustainability indicators on consumers' dietary decisions. For this, the study examines the connection between social, ecological, or economic factors of foods and current food consumption. Materials and methods are gathered and used within a case study of Germany.

The main research question addressed in this study is RQ1: Which factors of sustainability influence dietary behavior?

To represent the currently prevalent diet in Germany, the average annual consumption of kg food per capita is determined with data from the Bundesministerium für Ernährung und Landwirtschaft (BMEL, eng.: Federal Ministry of Food and Agriculture). This is used as the baseline average dietary style and is assessed and compared under different aspects of sustainability ((1) societal, (2) ecological, (3) economic) throughout this study. The indicator for (1) social sustainability is represented with health-related factors within diets. National dietary recommendations are used to determine to what extent the average German diet differs from meeting declared nutritional requirements. For this, both an omnivorous, as well as a plant-based diet is defined. The omnivorous diet is mapped by the recommendation of the Deutsche Gesellschaft für Ernährung (DGE, eng.: German Society for Nutrition), whilst the plant-based recommendation is outlined by the Giessen Vegan Food Pyramid (GVFP). The indicator for (2) ecological sustainability is environmental awareness. For this, organically produced food is defined as more ecologically sustainable compared to conventionally produced food. Therefore, the proportions of consumed organic food in Germany are examined, with data provided by the Verbrauchs- und Medienanalyse (VuMA, eng.: Consumptin and Media Analysis). Likewise, diets lower in animal products are defined as the more ecologically sustainable option. Therefore, proportions of different diets within the German population (namely omnivorous, vegetarian, and vegan diets) are examined, with data from the Allensbacher Markt und Werbeträgeranalyse (AWA, eng.: AllensbachMmarket and Advertising Media Analysis). To relate these proportions to sustainability awareness of German consumers, two surveys on attitudes towards social and ecological responsibility are considered, with data provided by VuMa. The indicator for (3) economic sustainability is food prices. For this, market research is carried out in different stores (namely a supermarket, a discounter, and an organic store) and for different price levels (namely cheap, middle-priced, and expensive). With all the aforementioned distinctions of possible diets (organic/conventional cultivation, plant-based/omnivore diet, supermarket/discounter/organic store, cheap/middle-priced/expensive product) shopping baskets are created and the prices of groceries within these baskets collected through the market research, which culminates in a survey size of 1446 grocery prices.

Results of the health-related dietary assessment show that the German average food consumption lacks nutrient-dense input whilst overemphasizing animal-based foods, and sugar. The consumption of vegetables and pulses is not even half as high as recommended. Only the intake of milk and dairy products or their alternatives is comparable in both dietary recommendations, and the currently prevalent German diet. Throughout the results of the environmentally focused dietary assessment an attitude-behavior gap of consumers becomes visible: whilst over half of the consumers report their interest in sustainable food consumption and production, less than one tenth of the German population consumes no meat (just over one percent follow a fully vegan diet), and little over one third of the people regularly purchase organically produced food. The economic assessment reveals firstly that a plant-based diet is generally more expensive than the omnivorous diet, whereas this gap is higher with fully conventional purchases (+41%) rather than with organic purchases where the plant-based diet is only 3% more expensive. Also, a fully organic diet is on average almost double as expensive as a fully conventional diet. On the other hand, when optimizing the health-indicators of one's diet and therefore purchasing food according to the dietary recommendations, both the recommended omnivorous, and vegan diet are well within financial reach of the average food expenditure of German consumers, with DGE being approximately 18% cheaper, and GVFP being about 2% cheaper. Including environmental aspects, in this contribution represented with organic foods, into the healthy diet would amount to a price increase of about 15% and 19% for the omnivorous and plant-based diet, respectively. This would burden the average German household per year with more than twice a monthly budget for groceries and hence represents rather large additional costs. Comparing the types of stores, results show that the cheapest option overall would be a conventional omnivorous diet purchased in the supermarket rather than the discounter that was initially expected to yield lowest prices overall. The most expensive option overall would be an organic plant-based diet purchased in the supermarket rather than the organic store. The bigger driver of price increase is a switch from conventional to organic produce, rather than the switch from omnivorous to plant-based diet.

These results suggest that both health, and environmental factors play a minor role in factual dietary purchasing decisions in Germany, even if the consumers' awareness and attitude point towards perceived importance of such issues. The price of food can present as one reason for the average German consumer to lean towards the purchase of omnivorous, conventionally produced diets. Given the comparably high prices of especially organically produced foods, there is no financial incentive for ecologically more sustainable dietary behavior. On the other hand, unsustainable food groups, especially conventional meat, are comparably low priced on the market and followed by rather high consumption levels. Takeaways of this study for policymakers are manifold: engaging more educational strategies to foster deeper understanding of both health-related and environmental impact from food consumption presumably wont hinder furthering observable trends towards holistically sustainable dietary behavior; however, economic incentives for sustainable production and consumption are pivotal for a sustainable dietary transition. Socially and ecologically sensible food baskets should also be economically beneficial for consumers and producers.

As introduced in section 1 of this work, TCA can be one such tool for setting economic incentives for sustainable food production and consumption. Therefore, RQ2 – What is the framework of TCA in the context of agricultural goods and how are market prices of food affected when adding external costs of production? – is addressed with the following three contributions presented in subsections 3.2 to 3.4.

3.2 Calculation of external climate costs for food highlights inadequate pricing of animal products

Contribution B focuses on the establishment of a framework to assess agricultural external costs that also enables a differentiation between farming systems and food categories. The proposed method is applied in the context of German agricultural production and for the calculation of specifically GHG related externalities.

The main research question addressed in this study is RQ2.1: How can climate costs of different foods and production practices be calculated and how do they relate to current market prices?

The framework developed in this work is divided into two steps: (1) quantification of GHG emissions, and (2) following monetization of GHG externalities. The system boundary of this assessment is from cradle to farmgate and therefore includes all preliminary processes, as well as processes on farm; downstream processes, like the transportation to processing plants or cooling of warehouses, are not included. For the quantification (1), LCA database GEMIS provides data for eleven conventionally produced foods (namely vegetables, fruits, cereals, root crops, legumes, oilseeds, eggs, poultry, ruminants, pork, and milk), which is used to determine specific GHG emissions of each foodstuff. A meta-analysis of literature comparing conventional to organic GHG emissions on farm scale enables the distinction of GEMIS data for organic food. LUC related GHG emissions are not included in GEMIS and therefore calculated with a method proposed by (Ponsioen and Blonk 2012) for conventional produce. LUC from the production of organic food is negligible in Germany and LUC related GHG emissions for organic products are hence not calculated. The eleven different datasets are aggregated with their German production share to the superordinate categories plant-based food, animal-based food, and dairy. Aggregation with production shares is also used for the determination of the average weighted producer price of these superordinate food groups. For the monetization (2), a damage cost rate of 180€ per ton of CO_2 as proposed by the German Federal Environmental Agency is used to determine the GHG related externalities for both the eleven specific foods, and the three superordinate food categories.

Results of the emission quantification (1) show that especially for animal-based foodstuff, GHG emissions per kg of product are exceptionally high: animal-based foods cause, on average, ten to 13 times the emissions of dairy, and even 67 to 122 times the emission of plant-based foods. Organic production causes fewer emissions in plant-based and dairy category due to stricter regulations, which benefits GHG emission levels. In the animal-based category, however, organic production causes higher emissions per kg of product without the inclusion of LUC emissions. This is explained with higher land use and living age for organic livestock, as well as lower productivity of organic feed. Including emissions from LUC flips this result for ruminant and pork however, for which now conventional production causes higher emissions. This is due to the animals' feed consumption causing LUC in foremost peripheral regions. Results of the monetization (2) show that external climate costs for organic plant-based foods are clearly the lowest (0.02€ per kg), followed by conventional plant-based foods with double the organic cost. Conventional dairy causes about 4 cents more climate costs per kg compared to organic dairy of 0.19€ per kg. The highest costs occur from both animal-based production practices, with 2.41€ per kg on average. Putting these results in relation to producer prices, necessary surcharges that include GHG costs into the market prices can be calculated. Organic plant-based foods are currently most sensibly priced compared to all other categories with a necessary surcharge of only 6%. Conventional plant-based foods would necessitate an increase of a quarter of the current market price. Organic dairy prices would rise by 40% with an inclusion of climate costs, followed by organic animal-based foods with 71%. Finally, conventional dairy causes climate costs of 91% of its current market price, almost doubling its cost, which is even surpassed by conventional animal-based foods entailing a price surcharge of 146%. The choice of farming system therefore has stronger influence on relative price increases since organic foods are consistently higher priced at the market currently. This is also because these prices include organic practices, which might be more costly for the farmer (e.g., producing feed on farm) but are beneficial for the avoidance of additional GHG emissions (e.g., no GHG from transportation of feed).

Appropriate pricing for food, with an inclusion of GHG costs, for example, would assist the increase of demand for organic foods: due to the consistently lower price surcharges for organic foods, their demand would fall to a smaller extent compared to demand for conventional foods with consistently higher price surcharges. This leads to a market advantage for all organic food categories. Since increases in costs of animal-based foods are highest over both practices, a following decrease in their demand would also release pressure on land capacities. This could in turn be used to counterbalance an alleged higher land use from an increase in organic production, which mostly requires more land than conventional production. Further advantages in demand shifts following the internalization of climate costs could be positive health effects for the individual and therefore lower national health-related expenditures. While a higher price leads to higher expenses for consumers, the generated income for the state through internalization of climate costs could be used for redistribution towards citizen strata that are financially less privileged and hence more burdened by high food prices.

The herein presented framework can be further extended and used in other application cases. For one, deeper understanding of LUC emission assessment is sensible since these affect externalities of animal-based products to a considerable extent. This is addressed within the work of subsection 3.3 and Contribution C. Also, as the framework herein used for GHG emissions, can be extended for the calculation of other externalities. This is done within the work of subsection 3.4 and Contribution D.

3.3 Land use change and dietary transitions – Addressing preventable climate and biodiversity damage

Contribution C focuses on global LUC caused by animal-based foods consumed in Germany. For this, in the study LUC related CO_2 emissions, as well as the associated biodiversity lost as deforestation, are calculated for feed and livestock exporting countries and different feed commodities. They are subsequently linked with German consumption levels. The study finally finds the costs Germany causes abroad due to the country's consumption of meat, dairy, and eggs when lastly LUC impacts are monetized.

The main research question addressed in this study is RQ2.2: What is the impact of global land use change from food consumption and what is its monetary damage?

The method used to quantify land area and CO_2 emissions from LUC of German animal-based food consumption is comprised of three models: (1) a land balance model allocates forest loss to newly formed pasture and cropland; (2) an emission model uses the previously quantified LUC to calculate carbon changes due to loss of biomass (above and below ground), and soil organic carbon; (3) a physical trade model tracks German consumption and import values along international trade routes of feed and animal-based products. Germanys LUC impacts can therefore be calculated when linking results of (1) and (2) with trade flows of (3). This method is based on an existing model of Pendrill et al. (2019) but expanded for this paper with the assessment of additional countries, more food products, and with a successive TCA. Feed crops included in the assessment are the most used feed in Germany, namely wheat, barley, maize, soybean, rape and mustard seed, and rye. A total of 127 countries are examined for LUC and their trade of feed or animal-based products related to Germany's consumption. The time frame of the assessment is 2013 through 2016. The animal-based products assessed for end results are beef and buffalo meat, goat and sheep meat, milk and dairy products, pork, poultry meat, and eggs. With the subsequential TCA, costs of carbon emissions and biodiversity loss are calculated from the results obtained through the connection of (1), (2), and (3). CO_2 emissions are monetized with the damage cost rate of 180€ per ton of CO_2 proposed by the German Federal Environmental agency as was used in Contribution B. For the monetization of biodiversity lost through deforestation a restoration cost factor was used. This was obtained within the project NEEDS (New Energy Externalities Development for Sustainability) funded by the European Commission and lies on average at 3.15€ per square meter of tropical forest changed to cropland.

Main results of impact quantification show that the greatest share of LUC related CO_2 emissions of German animal-based consumption is held by milk and milk products: even if per kg of product dairy causes the least emissions over all animal-based categories (0.09 t CO_2 per t of dairy), over 25 million tons are consumed annually; this amounts to over 2.17 million tons of CO_2 emissions from German dairy consumption annually and 5,759 hectares deforested globally. While beef causes highest emissions per kg (0.75 t CO_2 per t of beef), its consumption levels are lowest over all meats (except sheep and goat meat; their overall LUC impact is rather negligible). Eventually, about 1.12 million tons of CO_2 is emitted due to German beef consumption annually. Per ton of product, beef also induces the most deforestation at 22.4 square meter, almost 10 times as much area as is deforested for one ton of dairy. Overall, whilst 79% of in Germany consumed animal-based products are also produced in Germany, 72% of LUC related CO_2 emissions are emitted in the country itself. The rest originates elsewhere for German import. This gap is foremost explainable with ruminant meat, particularly beef: domestic production causes less than one third of CO_2 emissions compared to imported beef. In total, an area of more than 16 thousand hectares are deforested annually for German animal-based consumption. This is roughly the size of Liechtenstein, or more than half of the city of Munich. The main feedstock imported to Germany is rape and mustard seed, closely followed by soybeans. The biggest sourcing countries for these crops are Australia and Brazil, respectively. These groups of feed crops also cause disproportionally high LUC impacts compared to other crops. Main results of impact monetization show that the overall annual monetary damage caused by LUC for German animal-based consumption consist of 1.1 billion € for CO_2 emissions and 0.5 billion € for biodiversity lost on deforested area, amounting to 1.6 billion € per year. Major contributing groups are, likewise to the quantified impact, milk and dairy with almost 390 million €, pork with almost 350 million €, and beef with almost 150 million € annually.

The results of this work disclose potential for LUC induced impact mitigation. A shift in feed stock towards less harmful crops and more reliance on domestically produced protein can be beneficial. This, however, entails a transformation of the German agricultural sector to ensure near self-sufficient protein supply for livestock and people. A shift in human diets towards more plant-based protein rather than the large amounts of animal-based protein consumed currently is pivotal and most promising. Especially a reduction in dairy intake would help reducing global LUC impacts of Germany; but also reduced meat consumption would amplify such achievements. It remains clear that Germany cannot satisfy its consumption with nationally available resources. Animal-based consumption in Germany drives forest loss, particularly in South America and Australia. A monetization of LUC impacts globally, driven by German consumption, helps comparing different environmental aspects (e.g., CO_2 emissions and biodiversity loss, both driven by deforestation), and helps communicate its consequences to the consumer or even supports a shift in demand through market prices aligned with TCA principles.

This work helps to understand global implications of German animal-based consumption and shows different routes for LUC mitigation. Nevertheless, it only focuses on the impacts of LUC and falls short in exploring potentials that lie in shifts of production practices. Therefore, Contribution D and regarding section 3.4 will investigate this further.

3.4 True Cost Accounting of organic and conventional food production

Contribution D focuses on further devising the framework developed in Contribution B to bridge the gap between organic and conventional market prices by following the polluter pays principle. Full LCAs are therefore combined with a monetization of all midpoints for a comprehensive TCA of various foods and farming scenarios in Germany. Subsequently, these calculated environmental externalities are then internalized into current market prices.

The main research question addressed in this study is RQ2.3: How does an internalization of monetized environmental impacts for different food products and farming scenarios influence market prices?

This study combines full LCAs with TCA for a quantification of environmental external costs and to show market distortions. LCAs are conducted for 22 different foods produced in Germany. They are inherent to the categories of cereals, legumes, oilseeds, roots and pulses, meats, milk, and eggs. The functional unit is one kilogram of product. The foods' data is obtained from the LCA database Agri-Footprint 5.0 as the conventional base case, based on which the organic base case and four different organic production scenarios are modelled on LCI level. Differentiations in the models are implemented for yield, manure and crop residues, energy consumption, and livestock's life span and feed intake based on literature data. Differentiations for use of pesticides and fertilizers, and transport are modelled based on the EU Council regulation for organic farming. Impacts are assessed with the LCIA method of ReCiPe 2016. For a subsequent monetization, however, ReCiPe 2008 is used, as this is most compatible with the environmental costing method of the Environmental Prices Handbook (EPH) used for monetization. Costs within this assessment are mainly expressed as damage costs. To depict the great uncertainty persistent in environmental costing, next to the base case of EPH, we also evaluate 3 more costing scenarios. The combination of farming and costing scenarios gives 26 sensitivity analyses in addition to two base cases.

Main results of LCA show firstly that both the yield (meaning produced functional unit per hectare of agricultural production or per livestock unit), and the manure rates have great influence on the environmental impact of a product. Although yield rates are generally lower in organic production, organic scenarios entail less environmental impact for most midpoints (except land use, which specifically describes yield disadvantages) if manure rates are lower or equal compared to conventional production. Manure, however, influences results of some organic products for the worse when application rates are higher compared to conventional scenarios. To find further environmental hotspots in the foods' production we look at the process contributions towards all midpoints. Fertilizer has impact on, for example, global warming potential or terrestrial acidification in cereal production, but has little to no impact on terrestrial ecotoxicity, which is foremost impacted by plant protection like pesticides. In the animal-based categories we find the life stage of ruminants to impact global warming, fine particulate matter, and terrestrial acidification to a great extent. This contrasts with other livestock, where the life stage does not significantly influence global warming due to the lack of enteric fermentation during digestion and therefore lower methane emissions. For these categories, feed production mainly impacts this midpoint. Main results of the subsequential TCA show that the existing gap between lower conventional prices and higher organic prices cannot be bridged with internalizing environmental costs from LCA alone, especially in those categories where market prices differ strongly (legumes, and roots and pulses). An alignment of prices is observed for cereals, however, with oats reversing the market levels even. Also, sunflower seeds show lower organic prices after internalization. All animal-based products cause more external costs than any plant-based foods. For animal-based products, beef causes highest external costs. Compared to the current market price, the market distortion is also highest in this category: external costs are more than twice as high as the market price of organic beef, and more than 2.5-times as high as the market price of conventional beef. An alignment of organic and conventional market prices after internalization can be observed for animal-based products likewise.

Even if the environmental favorability of organic products is proven with LCA results, a following TCA is unable to express this economically by achieving lower organic market prices, foremost because the currently existing large price gap on the market cannot be compensated. Furthering this approach, therefore, can be the inclusion of pricing positive aspects, like ecosystem services (ES), alongside LCA results or even integrating ES into LCA to display organic environmental benefits sufficiently. However, the difference between plant- and animal-based foods does translate with TCA as well, which could foster dietary transitions towards more plant-heavy diets. Also, better representation of diversity in agricultural practices within LCA should be fostered in further research with an emphasis on primary data to better depict the variability in existing farming scenarios. A transparent differentiation of products and practices is pivotal to introduce TCA approaches into practice and to give consumers true options for their dietary decisions.

Contributions B through D establish and use the framework for calculating external costs of different products. The influence on market prices was observed rudimentarily. An implementation of TCA on the market, however, was not yet established. This is approached and explored within Contribution E and regarding section 3.5.

3.5 True Cost Accounting in agri-food networks: a German case study on informational campaigning and responsible implementation

Contribution E investigates an informational campaign of a German supermarket exploring TCA and its effects on consumer awareness in the food sector. Moreover, insights on socially just TCA implementation are gathered. For this, a consumer survey and expert interviews are interpreted to draw out potentials and obstacles of TCA as a communication tool and its factual implementation.

The main research question addressed in this study is RQ3: How does informational campaigning of TCA affect customers' perspective on dietary decisions and what are potentials and burdens of socially responsible TCA implementation?

The foundation of this study is the implementation of 'true price tags' for eight different foods (namely apples, potatoes, tomatoes, bananas, mozzarella cheese, gouda cheese, milk, and mixed minced meat) and two production practices (conventional and organic) in a supermarket in Berlin, Germany. Price tags were calculated in Michalke et al. (2020) and included an externality assessment of GHG emissions, reactive nitrogen emissions, energy use and LUC, calculated along the framework of Contribution B. Based on this, a (1) quantitative survey, and (2) expert interviews were conducted. For (1), a questionnaire of different sections (general purchasing behavior, familiarity with and perception of the campaign, willingness to pay, factors of interest for TCA, responsibility of implementation, change in consumption behavior) was designed and subsequently carried out as a face-to-face survey with 109 customers of said supermarket. The survey was representative for the German society based on gathered sociodemographic data. For (2), three expert interviews with practitioners in the field of TCA were performed and subsequently evaluated based on video-cued protocols. The interviews followed predesigned topics (the expert's TCA involvement, perception of acceptance and interest on the market, chances and risks of implementation, assessment of the campaign, discussion of survey results) and left room for further questions and discussion.

Main results show that the campaign design only partly enabled understanding of TCA and the context of agricultural externalities. Experts expected this and pointed out the preliminary insufficient awareness in societal discourse. They agree however, that sensibly designed campaigns can support a rise in awareness when utilizing TCA as a transparent communicational tool. To provide such transparency, experts appraise clear scientific consensus and further refinement of existing TCA methods as pivotal. It has to be distinguished between calculation and communication, however: whilst TCA calculation should be as precise as possible and as complex as necessary, TCA results should be communicated to consumers clearly and comprehensibly. This will also help support customers' willingness to pay for externalities. The survey showed, however, the higher external costs rose, the less willing they were to pay the 'true prices' of these products. Consequently, if TCA was implemented, most consumers stated to adjust their dietary behavior towards more sustainable – and consequentially cheaper – alternatives. This tendency was more pronounced when asked about increased organic consumption, rather than decreased animal-based consumption. This interest in sustainable transformation was mirrored, as almost all surveyed wished for an inclusion of ecological, social, and animal welfare factors through TCA into the current market design. For this, consumers foremost found the government responsible to work on policies of implementation and therefore act upon the general need for sustainability, also in agri-food networks. Likewise, experts perceive policy makers as mostly responsible to incentivize implementation of 'true prices' at the company level. They also describe TCA as an approach that enables integration of environmental and societal issues for sustainable economics and therefore a realization of the polluter pays principle. However, they warn about hasty implementation, especially focusing thereby on social injustice, which could arise from following higher costs of living especially for financially underprivileged social strata. This is mirrored by the consumers, who mostly referred to the price of products as the most important factor for purchasing decisions. Nevertheless, according to the experts, TCA should be combined with other political measures to drive sustainable transformation of agri-food networks.

Whilst a knowledge gap regarding agricultural externalities is still persistent, consumers' willingness for sustainable transformation of agri-food networks and likewise their own dietary behavior was proven. However, for full societal acceptance, TCA implementation must be designed in a socially just, and stakeholder-targeted (understandable) way to further encourage sustainable dietary behavior alongside contextual knowledge and resulting sustainability values. Legislators are expected to design policies of TCA that involve such issues of social injustice while likewise financially incentivizing both consumers, and companies, to transform their consumption and production sustainably. This political, societal, and business endeavor should be supported by research in and development of standardized and transparent TCA methods.

4

CONTRIBUTIONS

In this section, I present all constituent contributions with their title, authors, abstract, keywords (if applicable), and reference as one subsection. The full texts can be found in their according appendices, which are noted at the end of each subsection. For published contributions (A, B, E), the versions in print are attached. For accepted (C) and submitted (D) contributions, manuscript drafts are attached. All supplementary information is available in the electronic copy submitted with this dissertation.

Contribution A

Title: Influencing Factors for Sustainable Dietary Transformation – A Case Study of German Food Consumption

Authors: Nadine Seubelt, Amelie Michalke*, Tobias Gaugler

Abstract: In a case study of Germany, we examine current food consumption along the three pillars of sustainability to evaluate external factors that influence consumers' dietary decisions. We investigate to what extent diets meet nutritional requirements (social factor), the diets' environmental impact (ecological factor), and the food prices' influence on purchasing behavior (economic factor). For this, we compare two dietary recommendations (plant-based, omnivorous) with the status quo, and we examine different consumption styles (conventional, organic produce). Additionally, we evaluate 1446 prices of food items from three store types (organic store, supermarket, and discounter). With this, we are able to evaluate and compare 30 different food baskets along their health, environmental, and economic impact. Results show that purchasing decisions are only slightly influenced by health-related factors. Furthermore, few consumers align their diet with low environmental impact. In contrast, a large share of consumers opt for cheap foods, regardless of health and environmental consequences. We find that price is, arguably, the main factor in food choices from a sustainability standpoint. Action should be taken by policy makers to financially incentivize consumers in favor of healthy and environmentally friendly diets. Otherwise, the status quo further drives especially underprivileged consumers towards unhealthy and environmentally damaging consumption.

Keywords: sustainable consumption; dietary behavior; food markets; case study; sustainable transformation

Published in Foods 2022, 11, 227. https://doi.org/10.3390/foods11020227

Please find the published full text in **Appendix A**.

Contribution B

Title: Calculation of external climate costs for food highlights inadequate pricing of animal products

Authors: Maximilian Pieper*, Amelie Michalke, Tobias Gaugler

Abstract: Although the agricultural sector is globally a main emitter of greenhouse gases, thorough economic analysis of environmental and social externalities has not yet been conducted. Available research assessing agricultural external costs lacks a differentiation between farming systems and food categories. A method addressing this scientific gap is established in this paper and applied in the context of Germany. Using life-cycle assessment and meta-analytical approaches, we calculate the external climate costs of foodstuff. Results show that external greenhouse gas costs are highest for conventional and organic animal-based products (2.41€/kg product; 146% and 71% surcharge on producer price level), followed by conventional dairy products (0.24€/kg product; 91% surcharge) and lowest for organic plant-based products (0.02€/kg product; 6% surcharge). The large difference of relative external climate costs between food categories as well as the absolute external climate costs of the agricultural sector imply the urgency for policy measures that close the gap between current market prices and the true costs of food.

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Please find the published full text in **Appendix B**.

Contribution C

Title: Land use change and dietary transitions – Addressing preventable climate and biodiversity damage

Authors: Moritz Hentschl, Amelie Michalke*, Maximilian Pieper, Tobias Gaugler, Susanne Stoll-Kleemann

Abstract: Land use changes (LUC) cause a large share of anthropogenic greenhouse gas emissions and endanger global biodiversity. Although LUC appear mainly as loss of tropical rainforest, the drivers can be located in regions of the global north, importing large quantities of agricultural goods from tropical countries. The aim of this study is to quantify and monetize the LUC impact caused by consumption of animal-based food in Germany as a case study and subsequently explore potentials for dietary transitions. We calculate the LUC impacts related to German animal-based food consumption with a combination of a land-balance, emission, and physical trade model. In particular, we determine CO_2 emissions caused by LUC as well as therefore deforested areas with associated biodiversity losses. Following the true cost accounting approach (TCA), the calculated LUC impacts are then monetized in order to approximate the related external costs of German food consumption. Our results show that German consumption of animal products causes 16.4 kha of deforestation annually (investigation period from 2013 – 2016). Out of 6 analyzed product groups, the largest share of deforestation relates to milk (35%) and pork (33%), while, in terms of relative impact, beef has the highest climate impact from LUC with 0.75 tCO_2 per ton. Monetizing LUC externalities results in societal costs of 1.1 billion € (plus 0.5 billion € for biodiversity loss) annually caused by German food consumption of animal origin. Results also show that imported animal-based products emit only slightly more LUC related CO_2 emissions than those produced in Germany. There is a great urgency for political measures as well as shifts in consumer behavior if sustainability goals are to be achieved. Both sides need to strive for a dietary transition towards more plant-based diets

Keywords: Dietary transition, Land use change (LUC), True cost accounting (TCA), Virtual land use, Sustainable agriculture

Accepted for publication in Sustainability Science 2022

Please find the full manuscript in **Appendix C**.

Contribution D

Title: True Cost Accounting of organic and conventional food production

Authors: Amelie Michalke*, Sandra Köhler, Lukas Meßmann, Andrea Thorenz, Axel, Tuma, Tobias Gaugler

Abstract: Agricultural activities are one of the biggest polluters globally. Consumers are misled towards demand of unsustainable and inadequately priced foodstuff by an insufficient internalization of externalities. A shift in demand towards more sustainable dietary choices can lead the sustainable transition of agri-food networks. We introduce a framework that evaluates environmental damage economically: we connect environmental assessment of different foodstuff with the internalization of its monetary impact. Life Cycle Assessments of conventional and organic foods are linked with True Cost Accounting to adjust food prices regarding their environmental impacts. Using this framework for 22 German agricultural products, we find that on average, plant-based production causes externalities of about €0.79 per kg for conventional, and about €0.42 for organic products. Conventional dairy and eggs induce additional costs of about €1.29 per kg on average, while in organic systems, they cause about €1.10 more. Conventional meat causes externalities of €4.42 and organic meat about € 4.22 per kg, with beef generating the highest costs of all. Environmental favourability of organic products is confirmed but resulting organic market prices after internalization still exceed conventional prices. Externalities represent a negative impact on societal welfare, which should be addressed with policies supporting transparent pricing approaches.

Keywords: Dietary transition, Land use change (LUC), True cost accounting (TCA), Virtual land use, Sustainable agriculture

Submitted in Journal of Cleaner Production 2022

Please find the full manuscript in **Appendix D**.

Contribution E

Title: True cost accounting in agri-food networks: a German case study on informational campaigning and responsible implementation

Authors: Amelie Michalke*, Lennart Stein, Rosalie Fichtner, Tobias Gaugler, Susanne Stoll-Kleemann

Abstract: There is broad scientific consensus that current food systems are neither sustainable nor resilient: many agricultural practices are very resource-intensive and responsible for a large share of global emissions and loss of biodiversity. Consequently, current systems put large pressure on planetary boundaries. According to economic theory, food prices form when there is a balance between supply and demand. Yet, due to the neglect of negative external effects, effective prices are often far from representing the 'true costs'. Current studies show that especially animal-based foodstuff entails vast external costs that currently stay unaccounted for in market prices. Against this background, we explore how informational campaigning on agricultural externalities can contribute to consumer awareness and tolerance of this matter. Further, we investigate the socially just design of monetary incentives and their implementation potentials and challenges. This study builds on the informational campaign of a German supermarket displaying products with two price tags: one of the current market price and the other displaying the 'true' price, which includes several environmental externalities calculated with True Cost Accounting (TCA). Based on interpretations of a consumer survey and a number of expert interviews, in this article we approach the potentials and obstacles of TCA as a communication tool and the challenges of its factual implementation in agri-food networks. Our results show that consumers are generally interested in the topic of true food pricing and would to a certain extent be willing to pay 'true prices' of the inquired foods. However, insufficient transparency and unjust distribution of wealth are feared to bring about communication and social justice concerns in the implementation of TCA. When introducing TCA into current discourse, it is therefore important to develop measures that are socially cautious and backed by relevant legal framework conditions. This poses the chance to create a fair playing ('polluter pays') with a clear assignment of responsibilities to policy makers, and practitioners in addition to customers.

Keywords: True Cost Accounting (TCA), Agri-food networks, Sustainable production and consumption, Food policy, Dietary behavior, Food labeling

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Please find the published full text in **Appendix E**.

5

CONCLUSIONS

Lastly, I draw conclusions from all contributions directed towards stakeholders of society and politics (in subsection 5.1), as well as science (in subsection 5.2).

5.1 Added value of the research

Agriculturally borne detriment to nature and people is apparent and indisputable. Prevalent industrial agricultural practices deliver food at a price much higher than is currently paid by the consumer at checkout. These extra costs are borne by society in the form of environmental decay and worsening life conditions. For a sustainable transformation of the agricultural sector, a shift in dietary behavior is as important as an increase in sustainable production and practices. TCA is one approach to facilitate both these aims.

Whilst information on healthful and environmentally conscious diets is vastly available, current prevalent dietary patterns in core countries neither reflect nutritional nor environmental sustainability recommendations. Contrary to this, economic considerations drive consumers' dietary decisions. Comparably low prices for unsustainable products – e.g., conventionally produced meat – result in high demand thereof. Likewise, more sustainable purchases, like shopping baskets comprised of organic food, pose a financial burden for customers. For sustainable transformation of agricultural demand, an economic incentivization, pioneered by political decision makers and executed by businesses, is therefore paramount. With reflecting externalities of production within the market prices in a differentiated manner, economic purchasing decisions will likewise be environmentally and socially sustainable. This will facilitate consumers to follow up on their shown interest to consume sustainably. To support well informed dietary decisions, the calculation of externalities should be able to differentiate between production practices and food groups: considering environmental indicators reveals gaps between externalities of organic and conventional origin, and even more so between plant-based and animal-based foods. Hence, after implementing TCA in the food market, consumers' spending would increase to lesser degree relative to their current budget if they opted for organic, and plant-based products compared to conventional, and animal-based foods. A market design should be established, where the products' environmental advantages are also expressed within their prices as an increased interest in organic and plant-based production and consumption poses a chance for policy makers to reach goals of organic market shares. Dietary shifts towards more plant-heavy diets are likely when implementing "true" prices. This will support the achievement of both national and global sustainability goals. Responsibility of consuming countries from using global land resources and causing emissions globally to meet their national demand of foremost animal-based foods can be made visible through TCA likewise. This necessitates an implementation of TCA methods along full supply chains and across national borders. For this, an international political cooperation and communication, as well as societal discourse on this operative step towards global sustainability must be fostered.

5.2 Outlook and future research

Research on TCA is a rather novel strand of interdisciplinary sustainability science and one that can be evolved from different scientific disciplines. Generally, of course, the herein presented methods can be translated to other industrial sectors and must not remain within the realm of agricultural production and food consumption. Externalities of any other commodity, with necessary adjustments, can be calculated accordingly. Considering the natural sciences, further strides towards optimization of TCA calculations should be taken. It must be noted, for one, that the basis of environmental assessment, the LCA, foremost focuses on negative environmental effects. Alleged positive effects on the environment, which can occur in agricultural production (e.g., carbon sequestration), and which agricultural production also relies upon (e.g., pollination), are currently not included in the LCA methodology – neither as impact, nor as input (Alejandre et al. 2019). Such effects are commonly known as ecosystem services. Van der Werf et al. (2020), for example, describe indicators missing from LCA as land degradation, biodiversity losses, pesticide effects, and animal welfare. Further, a higher emphasis on the collection of primary data will improve LCA databases and help to better depict scenarios of production practice and location. Both these possible expansions of existing LCA methods will enable a better reflection of the heterogeneity and complexity of agricultural systems and finally facilitate more transparency in TCA calculation and communication. It also addresses questions from agricultural science, regarding possible routes of process optimization in agricultural practice. From an economic perspective, the monetization of environmental or social impacts should be further explored. Putting a price on market-less entities like natural capital will remain a difficult undertaking but one necessary considering today's transgression of ecosystem and society. It will also be interesting to follow upon the herein presented, and further cases of TCA implementation on societal and business level. Firstly, it should be investigated, how an introduction of "true" prices can truly transform dietary behavior and therefore ultimately the agricultural production landscape. Secondly, it is of interest how businesses can address this transformation of the food market within their practice and along their supply chains. Thirdly, new accounting principles should be explored, which can build upon and incorporate existing sustainability accounting standards like the Corporate Sustainability Reporting and Due Diligence Directive. This equally calls for work within political science, which should focus on the development of TCA measures that hold businesses and societal actors alike accountable for externalities, whilst likewise designing these measures in a socially responsible way.

Concluding, this doctoral thesis delivers insights into the motivation, the execution, and the implementation of TCA for food products. In five scientific publications, qualitative, quantitative, and monetary analyses of agricultural externalities and their initial implementation to the market are provided. Findings hereof can be used by political decision makers, and researchers to support a sustainable transformation of the agricultural sector.

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APPENDICES

Curriculum vitae

Personal data

Amelie Michalke

b. 15.04.1995, Schongau, Germany.

Education

since January 2020	PhD at the Chair of Sustainability Science and Applied Geography, University of Greifswald.
October 2017 to September 2019	Master's degree in Industrial Engineering, University of Augsburg. Graduation as Master of Science in September 2019.
October 2013 to September 2016	Bachelor's degree in Industrial Engineering, University of Augsburg. Graduated as Bachelor of Science in September 2016.
September 2006 to July 2013	Student at Mariengymnasium Kaufbeuren, graduated with Abitur in July 2013.
September 2001 to August 2006	Student at Kaufering primary school.

Professional Career

since September 2020	Research Associate, Chair of Sustainability Science and Applied Geography, University of Greifswald.
March to September 2020	Research Assistant, Chair of Production and Supply Chain Management, University of Augsburg.
November 2019 to April 2020	Service in gastronomy, Mom's Table, Augsburg.
March to December 2018	Research assistant, Tollwood GmbH, Munich.
April 2017 to April 2018	Student assistant, Professorship Rathgeber, University of Augsburg.

October 2015 to September 2016	Part-time job at Welz Accounting and Office Services, Landsberg am Lech.

Publications (published and accepted)

Gaugler, T., & Michalke, A. (2017). Was kosten uns lebensmittel wirklich? Ansätze zur internalisierung externer effekte der landwirtschaft am beispiel stickstoff. *GAIA-Ecological Perspectives for Science and Society*, *26*(2), 156-157.
Pieper, M., Michalke, A., & Gaugler, T. (2020). Calculation of external climate costs for food highlights inadequate pricing of animal products. *Nature communications*, *11*(1), 1-13.
Michalke, A., Stein, L., Fichtner, R., Gaugler, T., & Stoll-Kleemann, S. (2022). True cost accounting in agri-food networks: a German case study on informational campaigning and responsible implementation. *Sustainability Science*, 1-17.
Seubelt, N., Michalke, A., & Gaugler, T. (2022). Influencing factors for sustainable dietary transformation—a case study of German food consumption. *Foods*, *11*(2), 227.
Hentschl, M., Michalke, A., Pieper, M., Gaugler, T., Stoll-Kleemann, S. (2022). Land use change and dietary transitions ‑ Addressing preventable climate and biodiversity damage. Accepted for publication in: *Sustainability Science*, Special Issue “Dietary transitions and sustainability: current patterns and future trajectories”.

Publications (submitted)

Michalke, A., Köhler, S., Meßmann, L., Thorenz, A., Tuma, A., & Gaugler, T. (2022). True Cost Accounting of organic and conventional food production. Submitted in: *Journal of Cleaner Production.*

Awards

Winner of „Forschungspreis Bio-Lebensmittelwirtschaft 2018“ (today: BioThesis), award for the Best Bachelor Thesis (2.000 Euro).

Foreign languages, and experience abroad

Study abroad, Canada, Memorial University of Newfoundland, September to December 2019

English C2-level

Spanish basics

Eigenständigkeitserklärung

Hiermit erkläre ich, dass diese Arbeit bisher von mir weder an der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Greifswald noch einer anderen wissenschaftlichen Einrichtung zum Zwecke der Promotion eingereicht wurde.

Ferner erkläre ich, dass ich diese Arbeit selbstständig verfasst und keine anderen als die darin angegebenen Hilfsmittel und Hilfen benutzt und keine Textabschnitte eines Dritten ohne Kennzeichnung übernommen habe.

Datum:

Unterschrift:

Erklärung zur Abgabe einer elektronischen Kopie der Dissertation

Mathematisch-Naturwissenschaftliche Fakultät

Einverständniserklärung nach § 5 Abs. 1 Nr. c Promotionsordnung

Hiermit erkläre ich, dass von der Arbeit eine elektronische Kopie gefertigt und gespeichert werden darf, um unter Beachtung der datenschutzrechtlichen Vorschriften eine elektronische Überprüfung der Einhaltung der wissenschaftlichen Standards zu ermöglichen.

Datum:

Unterschrift:

Shares of the authors

Authors of submitted, accepted, or published contributions are depicted in the following. Corresponding Authors are marked with * next to their name.

Contribution A

Seubelt, N., Michalke, A.*, & Gaugler, T. (2022). Influencing Factors for Sustainable Dietary Transformation—A Case Study of German Food Consumption. *Foods*, 11(2), 227. DOI: 10.1007/s11625-022-01105-2

Seubelt, N.: 40%; **Michalke, A.: 40%**; Gaugler, T.: 20%

Contribution B

Pieper, M.*, Michalke, A., & Gaugler, T. (2020). Calculation of external climate costs for food highlights inadequate pricing of animal products. *Nature communications*, 11(1), 1-13. DOI: 10.1038/s41467-020-19474-6

Pieper, M.: 33%; **Michalke, A.: 33%**; Gaugler, T.: 33%

Contribution C

Hentschl, M., Michalke, A.*, Pieper, M., Gaugler, & Stoll-Kleemann, S. (2022). Land use change and dietary transitions – Addressing preventable climate and biodiversity damage. Accepted for publication in: *Sustainability Science*, Special Issue "Dietary transitions and sustainability: current patterns and future trajectories".

Hentschl, M.: 20%; **Michalke, A.: 20%**; Pieper, M.: 20%; Gaugler, T.: 20%; Stoll-Kleemann, S.: 20%

Contribution D

Michalke, A.*, Köhler, S., Meßmann, L., Thorenz, A., Tuma, A., & Gaugler, T. (2022). True Cost Accounting of organic and conventional food production. Submitted in: *Journal of Cleaner Production.*

Michalke, A.: 35%; Köhler, S.: 15%; Meßmann, L.: 15%; Thorenz, A.: 10%; Tuma, A.: 10%; Gaugler, T.: 15%

Contribution E

Michalke, A.*, Stein, L., Fichtner, R., Gaugler, T., & Stoll-Kleemann, S. (2022). True cost accounting in agri-food networks: a German case study on informational campaigning and responsible implementation. *Sustainability Science*, 1-17. DOI: 10.3390/foods11020227

Michalke, A.: 35%; Stein, L.: 20%; Fichtner, R.: 15%; Gaugler, T.: 15%; Stoll-Kleemann, S.: 15%

Appendix A

This paper was published in the Journal *Foods* in January 2022.

Please find the published text in the following pages.

foods

Article

Influencing Factors for Sustainable Dietary Transformation—A Case Study of German Food Consumption

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Abstract: In a case study of Germany, we examine current food consumption along the three pillars of sustainability to evaluate external factors that influence consumers' dietary decisions. We investigate to what extent diets meet nutritional requirements (social factor), the diets' environmental impact (ecological factor), and the food prices' influence on purchasing behavior (economic factor). For this, we compare two dietary recommendations (plant-based, omnivorous) with the status quo, and we examine different consumption styles (conventional, organic produce). Additionally, we evaluate 1446 prices of food items from three store types (organic store, supermarket, and discounter). With this, we are able to evaluate and compare 30 different food baskets along their health, environmental, and economic impact. Results show that purchasing decisions are only slightly influenced by health-related factors. Furthermore, few consumers align their diet with low environmental impact. In contrast, a large share of consumers opt for cheap foods, regardless of health and environmental consequences. We find that price is, arguably, the main factor in food choices from a sustainability standpoint. Action should be taken by policy makers to financially incentivize consumers in favor of healthy and environmentally friendly diets. Otherwise, the status quo further drives especially underprivileged consumers towards unhealthy and environmentally damaging consumption.

Keywords: sustainable consumption; dietary behavior; food markets; case study; sustainable transformation

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1. Introduction

Empty supermarket shelves, hoarding, and lack of food and hygiene products, such as pasta, yeast, or toilet paper in grocery stores [1] caused existential fears all over the world at the beginning of the Corona Pandemic. COVID-19 gave the industrialized population, in particular, a small glimpse of what it was like to worry about one's daily food supply, as was the case in the post-war era.

At the end of World War II, famine and resource scarcity plagued nations due to low agricultural yields and unstable food security. The top priority was defeating these resource shortages and ensuring stable food security without a focus on healthy and balanced nutrition just yet [2,3]. To reach these goals, the Food and Agriculture Organization (FAO) was founded in 1945 [4]. With the economic boom throughout the 20th-mid-century, fears of food insecurity subsided in the global north and, rather, led to overconsumption. In 1950–1960, for example, consumption of poultry meat tripled per capita per year, and pork consumption also increased from 19 to 30 kilos per capita per year in Germany [3]. As a result, obesity and associated diseases increased sharply [3]. This raised the question of which foods can benefit health and nutrition. As early as 1950, the first dietary guidelines were developed for this purpose, intended to help people align their lifestyles with healthy food choices. These guidelines did not change significantly over time [2]. Later on, the nutrition circle, created by the German Nutrition Society (DGE), was introduced in Germany as a didactic tool [5].

Simultaneously, while food intake and, thus, calorie intake increased physical labor and with it energy demand decreased with advancing technology. For example, the proportion of employees working office jobs steadily rises [6]. The heightened prosperity and a wide range of food choices and social pressure to opt for convenience foods rather than healthy options, increases the number of people suffering from malnutrition or overweight [7]. Scientists and institutes have been warning of the health risks of increased food consumption for years. With this, the supposed health industry seems to be booming [8], with sales of diet products increasing over 30% since 2013 [9]. Alongside this, the trend towards a meat-free diet is growing. In the last 6 years, the number of vegans in Germany has already increased by 33% [10]. Research also shows that a vegan diet brings health benefits and reduces diseases such as diabetes and cardiovascular disease [11–13]. More and more people are open to a healthy lifestyle based on a healthy and balanced diet [14], yet there are reasons (sociocultural, emotional, etc.), which can hold them back in doing so [15–18].

Against this background, the first research question arises: namely, to what extent the population in industrialized countries actually eats a healthy diet?

The scarcity of resources during and after World War II led policy makers and researchers to develop new innovations and advances in the food industry. As a policy tool for this, the Common Agricultural Policy (CAP) was introduced in the European Economic Community to increase food supply and facilitate access to it. The CAP has had a significant impact on food supply, food prices, and the environment. However, it has also had a major impact on the way food is produced [2]. The use of inorganic fertilizers, herbicides, and pesticides was necessary to achieve the required productivity. However, the attempt to avoid crop failure, increase yields, and thus, combat hunger has been accompanied by the exploitation and destruction of the earth.

Excessive agriculture consumes enormous amounts of water and land, endangered ecosystems, and causes a large amount of greenhouse gas emissions [4,19,20]. Nowadays, the food system is responsible for 15–31% of total greenhouse gas emissions in Europe [4,5]. In Germany, the share is estimated at 15–20% [5,21], which means about 1.7 tons of greenhouse gas emissions per capita.

In addition to the conventional farming methods known today, organic farming developed, aiming at environmentally friendly agriculture. Organic farming helps build soil fertility, maintain biodiversity, and reduce losses of nitrogen, phosphorus, and pesticides [22,23]. Although it is arguable if greenhouse gas pollution is lower compared to conventional agriculture [24], the environmental benefits, in terms of ecosystem services that organic farms provide, are an absolute good [22,25]. The trend towards environmentally conscious diets has been on the rise since the 2000s. This can be seen in the increasing sales of organic products: they have doubled in Germany since 2011 and are already at 14.99 million euros in 2020 [26]. Additionally, the demand for organically traded products can be seen in the growing number of organic farms. Currently, every 8th farm in Germany represents a form of organic farming, and already, 10.2% of agricultural land in Germany is farmed according to organic guidelines [27].

Alongside this, environmental awareness is reflected in changing eating habits of the population and environmental sustainability metrics have been identified as an important pillar in nutrition education [28]. As mentioned, the number of vegans, i.e., people who abstain from all products of animal origin, and vegetarians, who largely abstain from meat, is growing [29]. This is because it is precisely the production of animal foods that causes a significant proportion of environmental damage with its high demand for resources but low production efficiency [30]. Abstaining from eating animal foods would be an important step to reduce climate damage [13,19,24,31–33]. For example, a vegan diet causes 40% less carbon dioxide emissions and would cause an average of only 1040 kg of CO2 emissions per capita in Germany [34].

As sustainable development of basically all sectors is of rising importance and sustainable consumption of all goods is necessary [35], knowledge about the strong environmental impact of food is growing [36–39], and different population strata behave more or less sustainably in response to this [16]. The question that arises is whether knowledge is put to action and to what extent the population in industrialized countries does eat environmentally consciously?

New developments in the cultivation and production of food also impact its price. During the famine at the end of World War II, for example, the cost of food was still immense and large proportion of consumption expenditure was spent on food and beverages [40]. However, with the increasing economic growth, the situation turned, and within 100 years, the proportionate expenditures in Germany for food and beverages sank from 57% in 1900 to only 15% in 2000 [41]. Prices for food products have decreased in recent years due to better use of fertilizers and technology, and in turn, the average income has increased due to economic growth in industrialized countries. In fact, the higher the GDP, the lower the share of spending on food [42]]. Compared to other European countries, Germany is far below the average of consumer spending [40]. A reason for this could be economic incentives. Across all media outlets, the cheapest offers from grocery stores are advertised. Discounters, in particular, have been dueling for years with the lowest price promise, conveying to the consumer that food has to be cheap. Especially for people with low incomes, the price represents a decisive driver [43]. However, it's not just financially underprivileged people who are cutting back on the quality of their food. For example, in a qualitative survey in the UK, the cost of food was cited as the most common reason for eating unhealthily across all income groups [44].

Against the background of economic factors addressed here, the third and final research question arises: to what extent does the German population base their purchase decision on the price of food?

In summary, it is the aim of this study to identify the influence on consumers' food choices from three different aspects: diets are analyzed along the lines of (1) nutritional health, (2) impacts on the environment, as well as (3) market situation or food prices. On this basis it is discussed whether social, ecological, or economic factors impact consumption choices and to what extent qualitative guidelines or the market situation hold potential of improving consumers' dietary behavior.

The paper starts with a description of the methodology and the data. Following, results and findings are presented and discussed for a conclusion.

2. Materials and Methods

In the following, the methodology for determining social, ecological, and economic influences on food consumption are addressed. The method is used in a case study within the German context. However, it can be transferred to comparable geopolitical frames, in particular to other highly developed countries in the western world.

2.1. Goal and Scope Definition

First, national dietary recommendations defined by the DGE and the Giessen Vegan Food Pyramid (GVFP) are compared to current dietary habits for insight into a potential disparity between supposedly healthy eating and actually consumed diets. Next, current eating habits and purchasing behaviors are analyzed to paint a picture on the present level of environmentally conscious food consumption in Germany. The current average dietary habit is defined below as the status quo. Further dietary styles considered in this assessment are an omnivore (defined by the DGE) and a plant-based diet (defined by the GVFP). This is further combined with two different forms of production practice, namely conventional or organic production. The combination yields four types of purchasing styles: omnivorous and conventional, omnivorous and organic, plant-based and conventional, and lastly, plant-based and organic. Third, economic implications for consumers are examined. For this, the dietary status quo, as well as shopping baskets, defined based on previously mentioned purchasing styles, are evaluated regarding the foods' prices. Three different price levels for each product category are also investigated by tracing the actual market prices charged in three different types of grocery stores. This is done to depict consumers' varying financial means underlying their purchasing behavior. Resulting is a definition of 30 in the following so-called shopping baskets.

2.2. Methods and Data for the Social Consideration

To compare health aspects of food choices, a comparison is made between the current average German diet and two dietary recommendations of German associations, which represent an omnivorous (DGE) as well as a plant-based diet (GVFP). By considering a plant-based dietary recommendation, the status quo is compared with this allegedly more ecologically sustainable alternative. At the same time, a balanced plant-based diet is widely established as healthy due to the lack of consumption of meat and other animal products [11]. In fact, the consumption of meat, in particular, is associated with the risk of higher mortality, cardiovascular disease, and certain forms of cancer [12], which is why this comparison is used for the consideration of health effects caused by different dietary styles.

The current diet is presented on the basis of the annual per capita consumption of various foods, determined by the BMEL [45]. The dietary recommendations are based on the recommendations of the DGE for an omnivorous diet [46], as well as the GVFP [47] for a plant-based diet. These guidelines give quantities for food intake that guarantee sufficient supply of essential nutrients. The weight ranges given for each food were averaged to an accurate serving size for the average person. The diets are based on the following food categories: "Grain and Cereal Products", "Vegetable and Pulses", "Fruit and Nuts", "Milk and Milk products", "Milk and Milk product alternatives", "Eggs (shell weight)", "Meat, Sausage and Fish", "Additional Food", "Fats" and "Sugar" [45].

2.3. Methods and Data for the Ecological Consideration

As a second factor of influence on consumers' food choices, environmental awareness is analyzed. Different products have varying impact on the environment. Thus, a plant-based diet causes a much smaller ecological footprint than an omnivorous diet and can be considered an overall sustainable alternative [48–50]. Similarly, organic agricultural production does less damage to the environment than conventional processes, for example through the use of fewer pesticides and respect for biodiversity. It is, thus, broadly considered the more sustainable practice [2,25]. Therefore, the proportions of organic foods currently purchased in Germany are examined to determine the influence of the environmental factor on the consumers' choice of food. This survey is provided by the Verbrauchs und Medienanalyse (VuMA) [51,52]. Furthermore, the proportions of different diets within the German population—omnivorous, vegetarian, and vegan—are analyzed to draw conclusions about the extent to which ecological awareness already impacts eating habits. In this context, survey results are obtained by the Allensbacher Markt und Werbeträgeranalyse (AWA) [10]. In addition, the attitude of German consumers towards social and ecological responsibility is considered and is compared with the two previous surveys in order to relate the current ecological attitude of Germans to their consumer behavior. The survey data is also provided by VuMa [53].

2.4. Methods and Data for the Social Consideration

In order to identify how food prices influence consumers' dietary behavior, market research is carried out for the German food market. With this, current prices of groceries were determined. Therefore, different shopping baskets were created, as described previously, which contain a defined selection of products: The shopping baskets are based both on the previously mentioned omnivorous and plant-based dietary recommendation. Both recommendations contain amounts of the individual food groups within a certain range (which, depending on the food, is given e.g., in grams or pieces). These amounts also account for the necessary nutrient supply of one healthy adult. The weight ranges given for each food are averaged to provide an accurate serving size for the average person. Since the recommendations do not provide more detailed differentiation on the selection of specific fruits, vegetables, and meats, these were determined by the average per capita consumption of Germans [45,54] to represent current consumption decisions accurately. The amount of food is determined per one week and one person to provide good comparability. Table 1 presents the final shopping list, based on the nutritional recommendations of DGE (left column) and GVFP (right column).

Table 1. Shopping-list for an omnivorous diet (left column) and a plant-based diet (right column) calculated for one week and one person.

	Omnivorous Diet (DGE) [g/Week × Person]		Plant-Based Diet (GVFP) [g/Week × Person]	
Grain and Cereal Products, Potatoes	Bread	1575	Wholemeal Bread	656
	Cereal Flakes	193		
	Potatos	525	Potatos	1500
	Noodles	132	Wholemeal Noodles	725
	Rice	116	Rice (1)	355
Vegetables and Pulses (3,7)	Tomatos	680	Tomatos	1020
	Carrots, Red Beet	237	Carrots, Red Beet	355
	Onions	201	Onions	301
	Cucumber	166	Cucumber	250
	Lettuce (2)	138	Lettuce (2)	207
	White/ Red Cabbage	89	White/Red Cabbage	134
	Savoy, Kohlrabi, Chinese Cabbage	55	Savoy, Kohlrabi, Chinese Cabbage	83
	Beans	47	Beans	71
	Mushroom	47	Mushroom	70
	Cauliflower, Green Cabbage, Broccoli	47	Cauliflower, Green Cabbage, Broccoli	70
	Asparagus	43	Asparagus	64
	Spinach	33	Spinach	49
	Peas	30	Peas	45
	Leek	25	Leek	37
	Celery	22	Celery	33
	Brussels Sprout	8	Brussels Sprout	12
	Pulses	490	Pulses	158
Fruit and Nuts (7)	Apple	346	Appel	692
	Banana	187	Banana	375
	Grapes	81	Grapes	161
	Strawberry	60	Strawberry	121
	Peach	58	Peach	116
	Pear	39	Pear	78
	Cherry	38	Cherry	77
	Rasberry	18	Rasberry	35
	Blueberry	16	Blueberry	32
	Plums, Mirabelle	16	Plums, Mirabelle	31
	Apricot	13	Apricot	26
	Blackberry	3	Blackberry	7
	Nuts	175	Nuts	315

Table 1. *Cont.*

	Omnivorous Diet (DGE) [g/Week × Person]		Plant-Based Diet (GVFP) [g/Week × Person]	
Milk and Dairy Products or Alternatives	Milk	787	Soy-, Grain-, Nutdrink	1225
	Yoghurt, Quark, Kefir, Buttermilk	787	Yoghurt-Alternative	1225
	Cheese	385		
Meat, Sausage, Fish and Eggs (7)	Pork	126	/	
	Poultry	61		
	Beef	38		
	Sausage	225		
	Fish, low-fat	115		
	Fish, rich in fat	70		
	Egg	3 pieces		
Oil and Fat	Oil	88	Oil	126
	Butter	79	Linseed Oil	84
	Magarine	79		
Beverage	Water, High-Calcium	3500	Water, High-Calcium	3500
	Non-Alcoholic, Low-Energy Drink (4)	3500	Non-Alcoholic, Low-Energy Drink (4)	3500
	Coffee (5)	228	Coffee (5)	228
Addition	/		Nori	14
			Vitamin B- Supplements	n/a
			Tofu, Seitan, Lupins	263

The following additional assumptions were made in the selection of foods: (1) unlike within the DGE recommendation, unprocessed cereals were not considered here. This is because, on the one hand, rice represents the most important category within this group, and on the other hand, cereals are already represented with the category of bread. —(2) Differently from the data source [45], lettuce was not divided into the two categories "butterhead lettuce/iceberg lettuce" and "other lettuce" but was considered within one category, since supply of the different types of lettuce was not guaranteed in every store. —(3) Currants are not considered because they are only available seasonally and within a short time frame. —(4) Low-energy beverages are assumed to contain less than 10 kcal per 100 milliliters. —(5) One liter of coffee is assumed to require 65 g of coffee powder [55]. —(6) Contrary to the GVFP, tofu, seitan, and lupins are included in the group "in addition" to ensure comparability to DGE within the group "vegetables and pulses". —(7) "Other fruits", "other vegetables", and "other meats", which the BMEL additionally categorizes, were not considered, as they hold only a small share within the quantities of the individual groups. —(n/a).

The prices of the foods within those baskets were determined with a market analysis. For this, three different types of food stores were considered to portray the German food sector fairly accurately, as they offer groceries at different price levels. The stores considered are (a) a full range supermarket, (b) a discounter, and (c) an organic food store. In this case study, (a) is a REWE market, representing a large chain of 33,000 stores distributed throughout Germany; (b) is represented by the discounter LIDL, which operates 10,800 outlets in 32 countries; (c) is ebl-naturkost, a small-scale organic food store, with 30 branches located in Bavaria in the South of Germany [56].

Since a distinction was made between organic quality and conventional production, the latter is not found in (c) the organic market; prices for conventional products were hence only collected in stores (a) and (b).

There are several alternative products for the same food (e.g., a no-name product/ private label/ branded product). Prices within the predefined shopping baskets were collected for the cheapest, a middle-priced, and the most expensive offers within each store to depict the price dispersion within supermarkets. If less than three different price levels were available for one product, the lowest price was used to fill the gaps.

When products were only available in organic quality (even in stores (a) and (b)), prices for conventional products were taken as the available organic price. Even after supplementing some in-store unavailable product prices with prices listed within the stores' online shops, 10% of prices were still unavailable. The organic assortment was particularly small for the supermarket (a), and the discounter (b). These remaining missing prices were established on the basis of the average deviation between the organic store's (c) and the respective missing store's prices. A detailed description of the procedure, based on an example, can be found in the Appendix A.

To ensure comparability, the prices of the 61 products were collected over a period of only three weeks in spring 2021. They were collected as prices per kg, with the product size closest to the full kg selected for the market analysis. Finally, the total price of the shopping basket was calculated according to the identified prices per kilo and the respective dietary recommendations defining the baskets. This market analysis results in a total of 30 shopping baskets (Figure 1) and in a total survey size of 1446 prices.

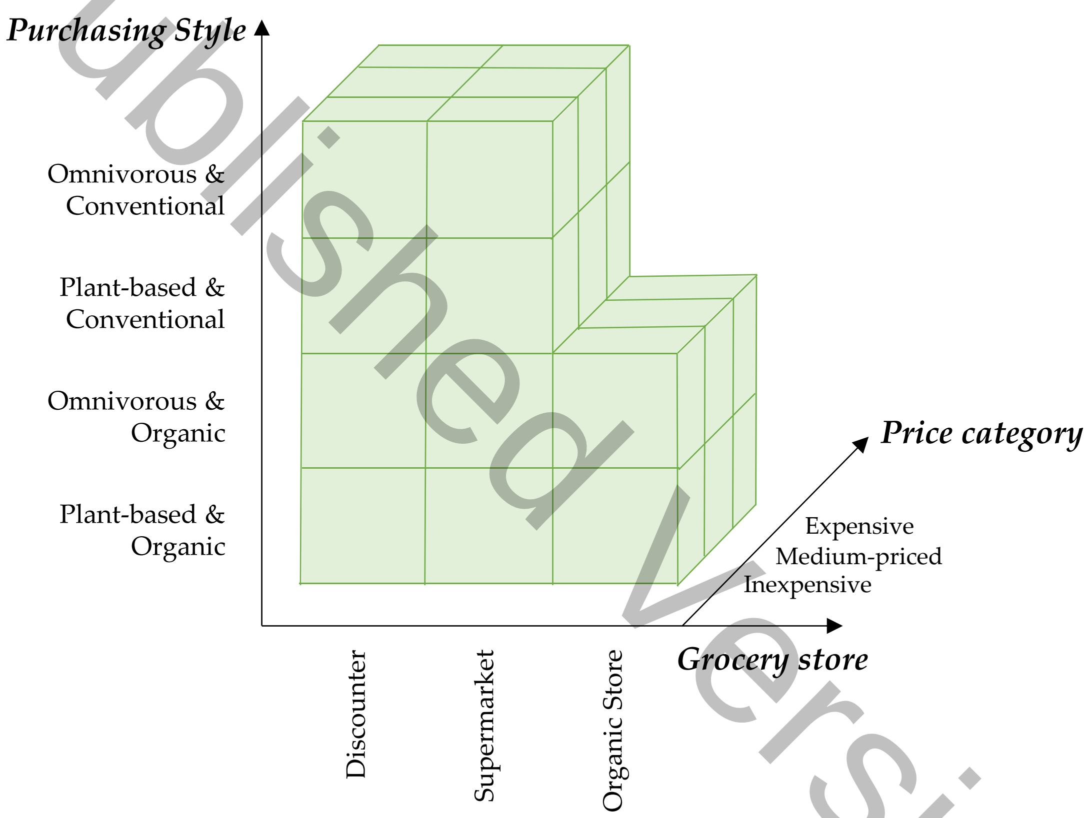


Figure 1. Pictorial representation of the 30 different shopping baskets. The three grocery stores are plotted on the x-axis. In each grocery store, an inexpensive, medium-priced, and expensive product was selected, which is plotted on the z-axis. On the y-axis, the four purchasing styles—omnivorous and conventional, omnivorous and organic, plant-based and conventional, and lastly, plant-based and organic. The organic store does not carry conventional products, so there are no corresponding shopping baskets for this intersection.

2.5. Uncertainty

Due to market, seasonal, and regional fluctuations, all prices collected are subject to a certain degree of inaccuracy. This is largely irrelevant for our market analysis since price volatility is taken into account to some extent: random price fluctuations would have an impact across all markets and would not reverse the final results and implications. Further, a wide variety of products is considered, which helps compensate for any extrema that might be occurring at the time the market was analyzed. However, seasonal fluctuations in market prices, or even in the general products' supply, are not considered. Shopping baskets further represent, as already mentioned, examples for the average German adult. Depending on one's individual preferences or habits, this is not representative for every citizen, but it is rather used for explanations and general. Further, the described calculation of missing prices represents only an approximation of the prices. However, this only affects a minor proportion of the prices surveyed (12%) and, otherwise, a large number of products could not have been included in the evaluation. Generally, it is arguable if only a comparison of plant-based vs. omnivorous and organic vs. conventional production is a sufficient metric to determine sustainability of different diets. There are other components to be considered in the context of food sustainability. However, to draw general conclusions, we decided to define this as an approximation to a sustainability metric for this paper.

3. Results

In the following, results from considering societal, environmental, as well as economic influencing factors on peoples' dietary choices are presented. Section 3.1 describes how health recommendations are comparable to the status quo. Furthermore, a closer look at current ecological performance of dietary specifications is given in Section 3.2. Finally, the price of all described dietary types is examined as an influencing factor on consumption behavior with the focus of results on the market analysis, presented in Section 3.3.

3.1. Social Consideration

Figure 2 shows the comparison of current dietary consumption and the recommendations of the DGE [30,46] and GVFP [47].

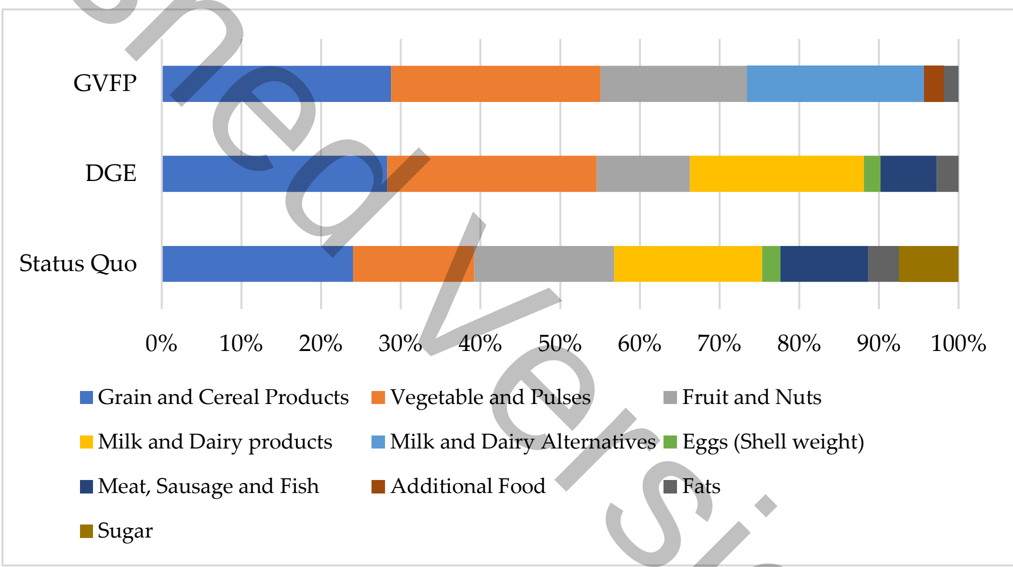


Figure 2. Relative per capita consumption in the status quo [45], and relative consumption recommendations of the DGE [46] and GVFP [47,57].

For all three cases, the four main food sources are cereal products, fruits, vegetables, and milk (products) or alternatives. It is apparent that the dietary status quo in Germany deviates from the health recommendations in many areas. The current average diet consists of 57% plant-based foods (excluding sugar and fats). The DGE recommends almost double the intake of vegetables and pulses (38%), resulting in a plant-based share of 66%. According to the GVFP, this share should even increase to almost three quarters (73%) of the total diet.

The proportion of milk and dairy products or their alternatives are rather comparable within the three diets, with 18.6% (status quo), 21.8% (DGE), and 22.2% (GVFP). The consumption of primary animal-based products, such as meat (products) and fish, is much higher than recommended with 0.705 kg more than described as the maximum intake by the DGE. The consumption of eggs and fats in Germany is currently also higher than recommended by both nutrition guidelines. In addition, sugar is consumed as 7% of the overall average diet, whereas it is completely excluded in both dietary recommendations.

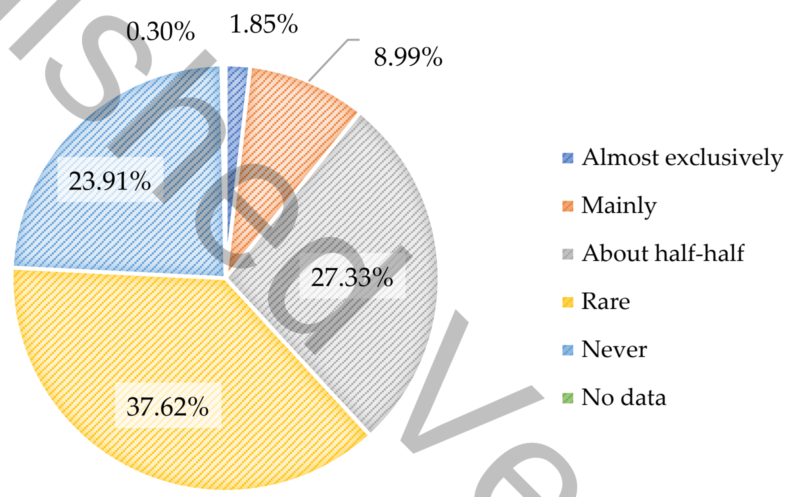
The lack of consumption of nutrient dense foods, such as vegetables or pulses, especially, indicate an unbalanced prevailing diet amongst the German population.

3.2. Ecological Consideration

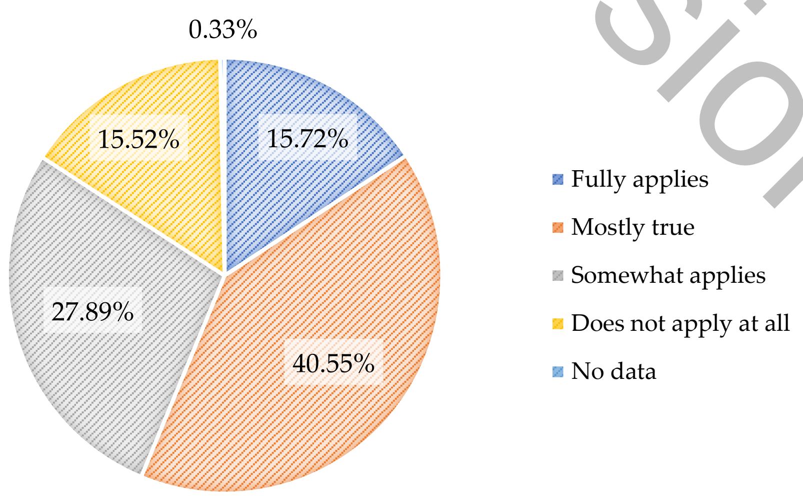
Subsequently, the current dietary consumption in Germany is analyzed regarding its ecological performance and whether this indicates an influence on consumers' dietary behavior.

Diet has a strong impact on the environment. High meat consumption is responsible for a significant amount of greenhouse gases, as well as water consumption [13,31,48,58]. Similarly, it is known that conventional farming causes higher damage to the environment compared to organic production [22,24,25]. Therefore, transitioning towards a plant-based and organic diet would be a valuable step in contributing to a healthy environment and fighting climate change [58].

Figure 3 shows the current proportions of diets, the share of German consumers buying organic foodstuff, and their attitudes towards socially and environmentally responsible products.

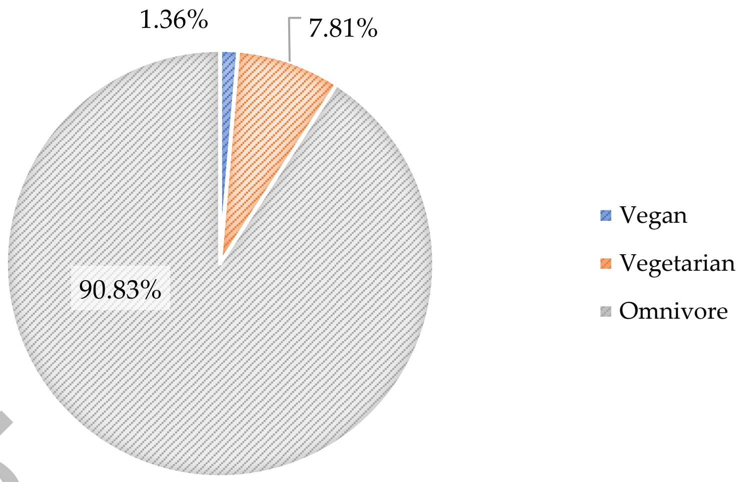


(**a**)



(**b**)

Figure 3. *Cont.*



(c)

Figure 3. (**a**) Population in Germany by extent of purchase of organic products [51] (**b**) Population in Germany by attitude toward the statement "When I buy products, it is important to me that the respective company acts in a socially and ecologically responsible. manner" [52,53] (**c**) Proportion of vegans and vegetarians in the total population of Germany in 2020 [29].

Figure 3 shows that only 38.2% of surveyed Germans regularly purchase organic products. The larger part, in contrast, states to rarely or never buy organic foods [29]. Despite the fact that the trend of meat-free diets has been increasing in recent years, this group still makes up no more than 9.2% of the total population of Germany [29]. Only 1.4% of Germans consume a vegan diet, which is considered most sustainable compared to omnivorous or vegetarian diets [10,50]. However, comparing these actual purchasing decisions with the consumers' statements on the importance of socially and ecologically produced products indicates a significant attitude-behavior gap: over half of surveyed people state their personal interest in a sustainably responsible way of producing as fully or mostly true. This gap has been shown by other studies likewise [15,16]. Even though social and ecological responsibility as a purchasing criterion has increased in recent years [52,53], this does not yet have a pertinent effect on German consumption behavior in buying organically grown products as a sustainable form of diet.

3.3. Economic Consideration

In this section, the results of the market research are analyzed as they are compared with the current average expenditure for food in Germany. The average expenditure of a German consumer is largely similar to the prices of the cheapest examined price level [59]. Therefore, only this price group is considered in detail below. The results of the remaining price levels can be found in the Supplementary Materials.

First, the price differences of the four purchasing styles—based upon the described dietary recommendations and agricultural production practices—are considered: plant-based (GVFP) and organic, plant-based and conventional, omnivorous (DGE) and organic, omnivorous and conventional, as well as the status quo of German food consumption. For this comparison, an average is calculated from the three store types considered. We find that, on average, a plant-based diet is 15% more expensive than an omnivorous diet. An organic purchase averages to almost double the price (+99%) than an otherwise identical basket of conventional products. Looking at Table 2, the price difference between omnivore and plant-based diets is larger when purchasing conventional products (+41%) than when opting for organic foods, where a plant-based diet is only slightly more expensive (+3%) than its omnivorous pendant. What is apparent, however, is the greater expense, when opting for the most sustainable shopping style, i.e., plant-based and organic: it is more than twice as expensive (+144%) than the more environmentally damaging conventional omnivorous shopping style.

Table 2. Costs of shopping baskets as an average of all stores.

Production Style/Dietary Style	Conventional [per Week × Person]	Organic [per Week × Person]	Difference Organic to Conventional	Average
Omnivorous	21.44 €	50.59 €	+136%	36.02 €
Plant-based	30.30 €	52.21 €	+72%	43.26 €
Difference plant-based to omnivorous	+41%	+3%	-	+15%
Average Price	25.87 €	51.50 €	+99%	38.64 €

The results in Figure 4 show that a diet based on the recommendations—either plant-based from DVFP, with an average of 43.26 €, or omnivorous from DGE, with an average of 36.02 €—is well within the average expenditure on food among Germans (44 € on average). However, it is also clear that the average consumer would need to invest at least 15% more for healthy and environmentally sound procurement.

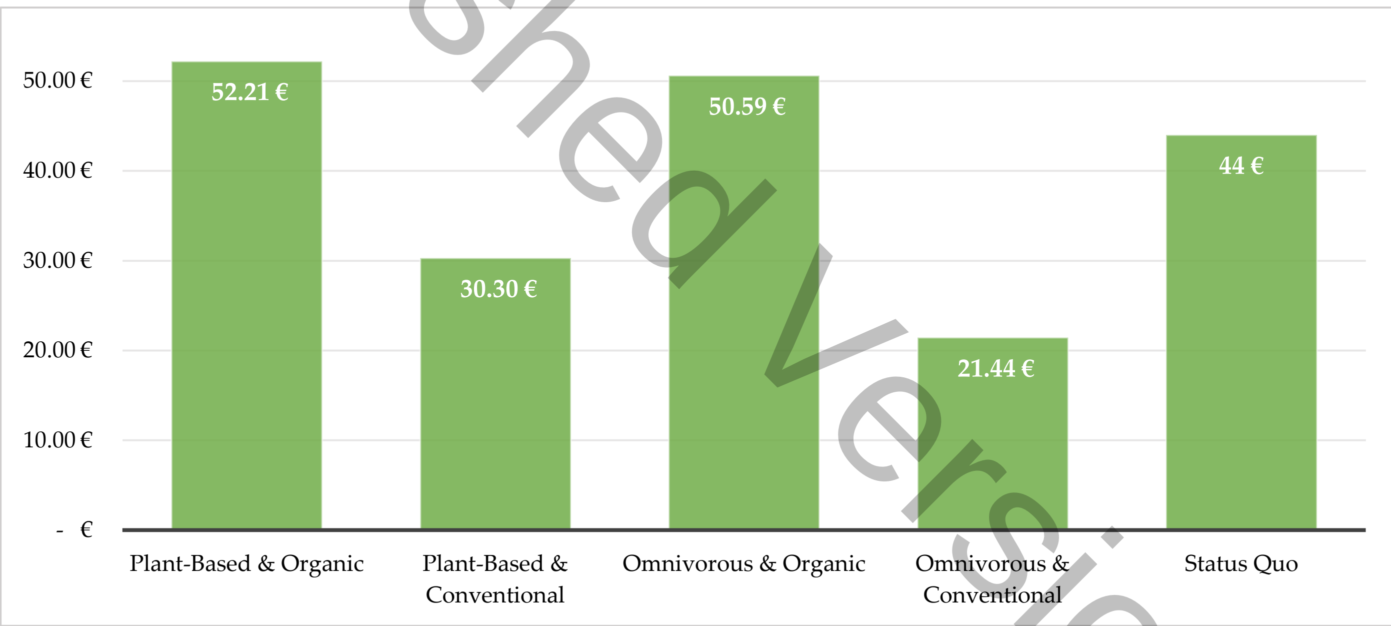
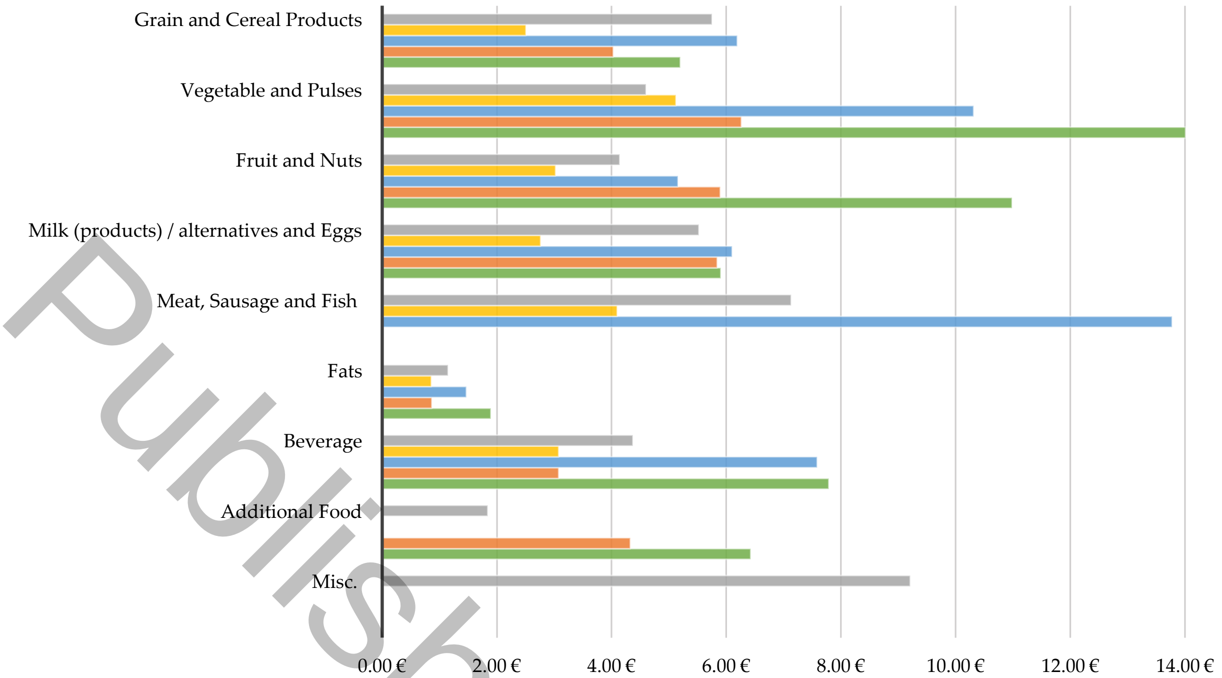


Figure 4. Costs of shopping baskets as an average of all stores, as well as the current average expenditure of Germans on food and beverages (Status Quo).

When purchasing conventional products only, a healthy, and partly sustainable (plant-based) diet can be afforded well within current expenditure for food. However, if sustainable production practices (organic) are to be taken into consideration as well, a 6.59 € (omnivorous) or 8.21 € (plant-based) price increase per week is expected compared to current expenses. This amounts to about 343 €, or about 427 € per year for an omnivorous or vegan diet, respectively. For one average household (1.99 capita), this would mean about 683 €, or 850 € of additional expenses per year. In both cases, this is more than twice a monthly grocery budget and represents rather large additional costs.

To work out the differences between the purchasing decisions in more detail, a look is taken at the food groups and cultivation forms within the different dietary styles, as well as the current average expenses of German consumers (Table 2 and Figure 5).



	Misc.	Additional Food	Beverage	Fats	Meat, Sausage and Fish	Milk (products) / alternatives and Eggs	Fruit and Nuts	Vegetable and Pulses	Grain and Cereal Products
Status Quo	9.21 €	1.84 €	4.37 €	1.15 €	7.13 €	5.52 €	4.14 €	4.60 €	5.75 €
Omnivorous & Conventional	- €	- €	3.08 €	0.85 €	4.10 €	2.76 €	3.02 €	5.12 €	2.51 €
Omnivorous & Organic	- €	- €	7.58 €	1.47 €	13.78 €	6.10 €	5.16 €	10.31 €	6.19 €
Plant-Based & Conventional	- €	4.33 €	3.08 €	0.86 €	- €	5.84 €	5.89 €	6.26 €	4.03 €
Plant-Based & Organic	- €	6.43 €	7.79 €	1.89 €	- €	5.90 €	10.98 €	14.01 €	5.20 €

Figure 5. Average prices of the dietary styles separated into different food groups, as well as the current average expenses in Germany [59]. Misc. = miscellaneous; 1 Sugar and confectionery, alcoholic beverage, and Tobacco [60].

At first glance, organic meat products, as well as organic vegetables and pulses, make up the most expensive food groups. This leads to a similar price for omnivorous or plant-based diets when purchasing organically.

The difference between the plant-based and omnivorous diet for plant-based foods overall is striking, as the expenditure for fruit within a plant-based diet is twice as high as within an omnivorous diet. This is reasonable, considering that, according to the dietary recommendation for plant-based nutrition, this diet requires almost twice the amount of fruit as the omnivorous recommendation suggests. The amount of vegetables is also 67% higher within the plant-based recommended diet.

Germans consume twice the amount of meat that the DGE recommends as the maximum. However, the current average expenditure for meat is just over half the cost it would be if meat were bought in organic quality and in quantity recommended by the DGE. Similarly, spending on fruit and vegetables of almost all purchasing styles is below the minimum cost needed within a diet covering nutritional recommendations. This result is consistent with the finding that German average fruit and vegetable consumption is currently below the dietary recommendations. In addition, spending on other items such as sweets, alcohol, and tobacco is particularly high, at almost 10 €, and represents the highest price share within the status quo. This expenditure is not covered in any of the dietary recommendations and hence increases the cost of current dietary behavior.

In the following, the different types of cultivation are highlighted. Table 3 shows the average prices of the different food groups for both conventional and organic production. It also shows the percentage deviation of the organic price to the conventional price. Looking at Table 3, causes of the high price difference in the omnivorous diet become apparent: The organic group of meat, sausage, fish, and eggs is by far the most expensive group. In comparison, the price of conventional meat, sausage, fish, and egg is far below at only 30% of the organic price. A very small difference, however, is visible within the group of dairy product alternatives. Since the stores' house brands are often produced in organic quality, the price for such alternatives is quite low within the organic group (Supplementary Materials). In addition, conventional plant-based food alternatives are oftentimes brand products, which are higher priced generally and thus create a balance between the organic and conventional product prices.

Table 3. Average price per kilo of food groups from all stores, divided into organic and conventional production. Presented is only the cheapest price category.

Groups/Average	Conventional [per kg]	Organic [per kg]	Difference Organic to Conventional
Grain and Cereal Products, Potatoes	1.49 €	2.50 €	+68%
Vegetables and Pulses	2.06 €	4.57 €	+122%
Fruits and Nutzs	5.25 €	7.08 €	+35%
Milk and Dairy Products	0.75 €	1.36 €	+82%
Meat, Sausage, Fish and Eggs	5.22 €	17.63 €	+238%
Oils and Fats	4.80 €	12.50 €	+161%

At last, the price differences between the three grocery stores are discussed. As can be seen in Figure 6, a conventional purchase, based on an omnivorous diet, is cheapest in the supermarket at 20.98 €. This is surprising, since shopping at a discounter would be anticipated to yield the lowest prices. However, with a maximum difference of 14% (between discounter and organic store in category omnivorous and organic), the three stores are at similar price levels in the individual dietary and purchasing styles. If one decides to buy organic quality, it makes little difference in the supermarket whether they consume a plant-based or omnivorous diet; in the organic store, a plant-based purchase even performs better than an omnivorous diet, which may be due to the high meat prices. At the discounter, however, it presents as rather the opposite to this. An organic purchase in the organic store also does not necessarily have to be the most expensive; a plant-based organic diet purchased in the supermarket is more expensive.

Table A4 in Appendix B provides a more detailed overview of the prices within the different purchasing styles for each grocery store and food category. In addition, it contains the information on the current average expenditure of a German consumer (status quo). Firstly, it shows that expenditure for omnivorous and conventional products, from both supermarket and discounter, are similarly high to the current average expenditure, while the organic expenditure turns out to be more expensive generally. In the cereal and meat product categories, larger price differences between the current average spending, and omnivore and conventional prices can be observed for the supermarket and the discounter. Thus, the average expenditures in these categories are significantly higher than the required expenses for consuming a nutritionally sound diet.

Figure 7 takes a closer look at the differences between animal products from the individual stores. It is noticeable that organic milk is, at most, half as expensive as its conventional pendant. It also shows that the price in the organic store is the highest in most cases. The organic store purchases most animal products from regional farms, which might be a reason for the higher prices. The cheapest conventional meat is sold by the discounter; the supermarket is cheaper for organic fish and sausage, however. Poultry and pork tend to be cheaper than beef over all grocery stores.

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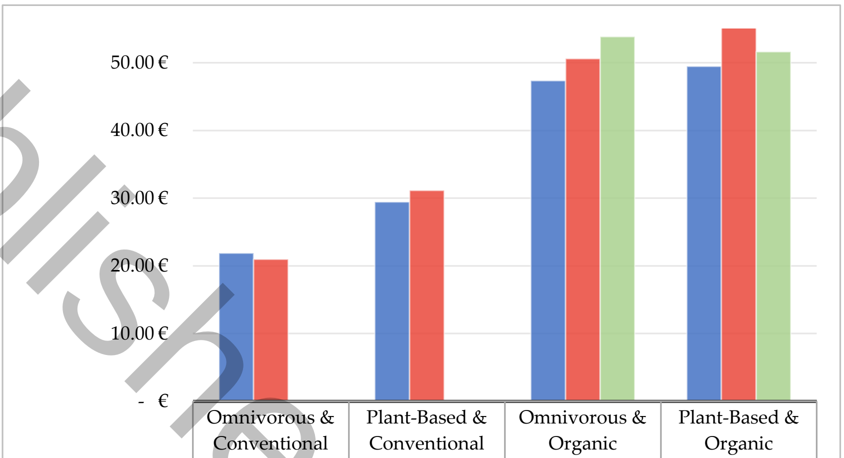

	Omnivorous & Conventional	Plant-Based & Conventional	Omnivorous & Organic	Plant-Based & Organic
Discounter	21.89 €	29.44 €	47.34 €	49.48 €
Supermarket	20.98 €	31.15 €	50.59 €	55.53 €
Organic store			53.85 €	51.60 €

Figure 6. Prices for the shopping baskets for each grocery store.

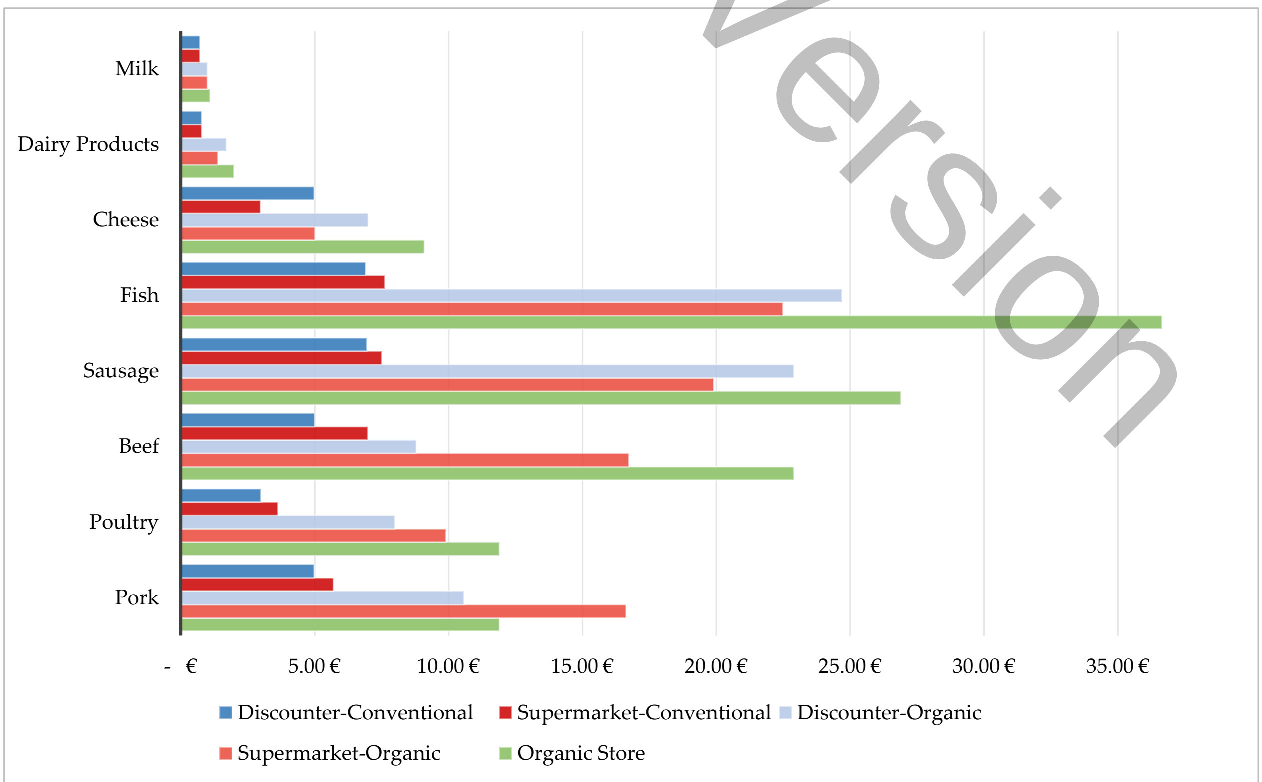

Figure 7. Prices per kilogram for the animal products for each grocery shop.

4. Discussion

Firstly, we find a clear deviation of current shopping behavior from dietary recommendations. It is reasonable to assume that the examined factor—one's own health—plays a minor role in food selection. The average German diet deviates from the recommendations, notably, in an excessive consumption of fat, sugar, and meat products. Dietary guidelines are currently available for 90 countries [61], which, as shown in 3.1, fail to motivate consumers to follow healthy eating habits. This could be because an individual's food choice is influenced by a multitude of indicators: biological reasons (e.g., intolerances), social factors (e.g., food-related traditions, social identity, awareness, economic situation) [62–65], or a constant exposure to external cues to food (e.g., easy access high calorie foods, diet-related media) [66] have shown to complicate healthy eating endeavors.

The increasing number of vegans suggests that awareness about the diets' influence on the environment paves the way for environmentally sustainable dietary transitions, but the number of plant-based eaters is too low to establish the environmental factor of significant influence on the choice of food. Further, our results show that the growing, yet too low interest in ecologically produced food also supports this assumption. There is an attitude behavior gap, as even though more than half of German citizens want to buy environmentally sensible products, only about one third show this attentiveness by buying at least some organic products. Accordingly, various reasons must lead to this large discrepancy and prevent people from consuming in an environmentally conscious way. O'Riordan and Stoll-Kleemann (2015) [15], for example, conclude that one barrier to shifting diets towards more plant-based consumption is the aversion of policy makers or practitioners (e.g., food retail) to promote such kind of behavior as it is delicate to communicate to voters or risking economic profit for companies. It is also important to consider that peoples' emotions, or sociocultural factors, can hold them back from consuming less animal-based foods [18].

This transitions well to the third part of this study: assessing the economic factor along its influence on food choices. The fact that the price of food has a strong influence on food choices is consistent with a qualitative study in the UK by Puddephatt et al. [44]. Our results indicate that the generally higher costs of plant-based and organic products seem to be an important reason for the rather unhealthy, environmentally unfriendly status quo and why an omnivorous, conventional shopping basket is preferred by the average German customer. Because organic products cost, on average, twice as much as conventionally produced ones, and a plant-based diet on average is 15% more expensive than an omnivorous diet, it is clear that there is no financial incentive given for buying more sustainably. Further, if one chooses to follow an omnivorous diet, an economic incentive is not set regarding organically produced meat: they are faced with more than double the cost of current meat expenditure, when following the DGE recommendation, which even suggests lower meat consumption than the status quo, and purchasing organic meat. Hence, one must be able to afford a sustainable purchase. On average, Germans spend 14% of their income on food, beverages, and tobacco [60]. The absolute spendable sum can be restrictive for people with lower incomes. Thus, factoring in sustainability when purchasing food is likely to be a luxury decision.

However, it is observed that the expenditure for a healthy diet, based on both the recommendations of the DGE (21.44 €) and the GVFP (30.30 €), is lower than the average German expenditure on food and beverages per week (44 €). Although these prices do not apply to organic quality, it is still possible to consume a healthy diet at a reasonable cost in Germany. Results show that currently, German consumers spend too small a share of their food expenses on fruit and vegetables. A predominantly environmentally sustainable diet can also be obtained, rather inexpensively, on the basis of the GVFP. This is in line with Macdiarmind et al. (2012) [67] who also find that a nutritious diet, which reduces impacts to climate compared to the status quo, can be consumed without raising costs for the consumer. Additionally, it can be seen that 14% of the actual food expenses alone are attributable to the consumption of sugar and confectionery, alcoholic beverages, and tobacco currently. What is interesting, is that these costs hold the highest share in food expenses overall (over 10 €); this economic weight does not seem to drive consumers away from such consumption habits. By reducing the level of consumption of these foods, customers could save money to invest in more environmentally friendly and health-conscious food alternatives.

When looking at the results regarding the different types of retail stores, it is evident that organic food is not necessarily more expensive in an exclusively organic market; fruit, vegetables or even cereal products are cheaper in the organic market or at a similar price level compared to the discounter and the supermarket. In addition, the organic market offers a larger selection of organic products. It also offers more regional and unpackaged products, which makes the purchase even more sustainable.

Interestingly, the cheapest shopping basket is not offered by the discounter, as would be expected. An omnivorous and conventional basket purchased in the supermarket induces the fewest expenses for customers. This is due to the higher costs for vegetables and fruits in the discounter, which are offered at a smaller price in the supermarket. Fruits and vegetables that have a particularly high share, such as tomatoes, apples, or grapes, are cheaper at the supermarket. However, these prices for fruit and vegetables are especially subject to seasonal price fluctuations and can differ when assessing the shopping baskets at different points in time. For all other food baskets, however, the discounter provides the cheapest option for consumers.

5. Conclusions

This paper set out to analyze three different possible influencing factors on consumers' dietary decisions. This work first provides some perspective on the overlap of sustainably preferable dietary patterns—concerning health and environmental favorability—and the actual consumption habits of the German population. It focuses, however, on the correlation between foods' prices and amounts purchased. This gives insight on shortcomings of the current food market and whether it is designed to support holistically sustainable food consumption. It is groundwork for further research in the context of dietary transitions, and it can function as food for thought for policy makers.

This work shows that the currently prevailing diet of the average German customer is not quite at the nourishing level that renowned dietary recommendations suggest. It is debatable whether more educational campaigns will help foster a transition towards healthier dietary patterns. It could be that yet more information within the context "health and diet" will overwhelm consumers with an already oversaturated market of ever changing "diet wisdom". What remains clear, however, is that insufficient consumption of fruit and vegetables contrasts, exceeding consumption of sugar and fats within the average German diet, as is the prevailing case in developed countries generally. This should be taken seriously when aiming at campaigns for healthy consumption and also in regulations of food marketing, which oftentimes advertises for unhealthy, highly processed products. In addition, nutrition education can help to develop appropriate educational strategies to achieve healthy eating behavior [68].

There is a trend towards more environmentally conscious diets amongst German consumers. However, an attitude-behavior-gap shows between consumers claiming to be invested in environmentally sound products and their actual lacking consumption of such. Moreover, this eco-conscious trend cannot yet contradict the detriment to the environment caused by production practices that have been established throughout the intensification of agriculture in recent decades. Again, the impact of informational campaigning alone is debatable. However, raising peoples' knowledge of the food-environment context will definitely not hinder sustainable dietary transition and should, likewise, be fostered by policy makers.

Both on health and environmental level, further research should investigate motivation and willingness to change from different consumer strata. This will provide information on how to best foster dietary transitions for policy-makers and practitioners alike.

Since information on diet alone seemingly has no sufficient effect on a sustainable transition of consumption patterns, the cost of groceries might influence dietary decisions. Our results show that low prices of unsustainable options, as is the case for conventional meat for example, are reflected in high consumption levels of these categories. Further, the market analysis showed that both a plant-based and omnivorous shopping basket with exclusively organic products exceeds current spending for the average German diet. This might explain the described lack of organic purchases contrary to the interest shown by consumers: the higher price of organic food is a burden many are not willing or able to overcome even if environmental impacts could be reduced. It should be a priority for policy-makers to redirect food production towards more sustainable practices and incentivize a transition towards, e.g., organic production.

Results show, however, that a nutritionally adequate diet, and even a more sustainable plant-based diet, can be purchased for lower expenses than is currently spent for the average diet. This suggests that knowledge of dietary contexts and adequate pricing can be overpowered by external factors, such as marketing for unhealthy alternatives or social pressure to partake in certain consumption.

Leaving all responsibility for a sustainable transformation of the food sector with the customer seems insufficient. Therefore, policymakers need to build upon this momentum. The already accelerated trend towards healthier, environmentally sensible dietary patterns should be fostered with adequate economic incentives: beneficial effects—or a lack of external costs—should be represented within the products' prices likewise. Increasing the price of unhealthy and environmentally harmful food, whilst subsidizing healthy and environmentally friendly food, could change the current price structure. The political goal should be sustainable food as the cheapest option for the consumer. This would also be desirable because financially underprivileged parts of the population would no longer be economically compelled to consume unsustainable diets.

Although the price structure of food sectors in other countries, especially in the allegedly developed world, seems comparable to data collected for Germany in this paper, food in Germany is comparatively cheap. This makes it difficult to transfer the herein presented results to other countries. Against this background, the aim of further research should be international market analyses and subsequent comparison of the country-specific results. Further, although we were able to describe a correlation between, e.g., low prices with high consumption of certain products, conclusions on causality are limited. This should be fostered in further research to find how price elasticities influence consumption behavior in detail. While data for food prices was selected from different price levels, the analysis on current consumption patterns do not differentiate between certain population strata. There might be differences in dietary behavior regarding socio-demographic factors, which will also be an interesting approach for further research. Based on this, investigating best practices for transforming dietary trends towards health and ecological sustainability, considering the circumstances of society, seems a sensible research trajectory.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/foods11020227/s1.

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Appendix A

Missing prices were calculated on the basis of a surcharge category. For this purpose, the shopping baskets of the organic store served as a reference value, since it is the only one to receive a complete organic shopping cart. In order to obtain a more accurate price calculation, the vegetable and omnivore shopping baskets were considered separately. To describe the procedure in detail, a calculation example is used in the following.

In the first step, all kilo prices of the same foodstuffs are listed.

Category: plant-based, organic, cheapest price

Table A1. Example explaining the methodology: Absolute prices of cucumber, lettuce and white/red cabbage listed in the three different types of stores (supermarket, discounter und organic store).

Store	Supermarket	Discounter	Organic Store
Cucumber	1.59 €	1.76 €	2.48 €
Lettuce	9.30 €	14.90 €	5.60 €
White/Red Cabbage			1.98 €

There is no offer and therefore no price available for white/red cabbage both in the supermarket as well as in the discounter.

The prices for cucumber, as well as for lettuce could be observed in all markets. In two stores, however, the price of white/ red cabbage is missing. These two prices are to be approximated now. Since the organic store has listed all products and their prices, its prices are the base prices, on the basis of which the price differences to the other shops are calculated. This procedure is illustrated again using an example in the next step.

Table A2. Example explaining the methodology: calculation of relative price differences.

Store	Supermarket	Discounter	Organic Store
Cucumber	−36%	−29%	0%
Lettuce	+66%	+166%	0%
White/Red Cabbage			0%
Average	+15%	+69%	0%

Cucumber is 36% cheaper at the supermarket than at the organic store, but lettuce is 66% more expensive. In the next step, the average value is calculated, which results from the two percentage differences for the supermarket and the discounter respectively. Thus, the prices in the supermarket are approximated on the basis of the two products, which—on average—are 15% more expensive than in the organic store. These mean values form the factor for the respective store, with which the missing prices are calculated in the last step on the basis of the organic store price.

Table A3. Example explaining the methodology: Absolute prices calculated based on our estimation method.

Store	Supermarket	Discounter	Organic Store
Cucumber	1.59 €	1.76 €	2.48 €
Lettuce	9.30 €	14.90 €	5.60 €
White/Red Cabbage	2.13 €	2.67 €	1.98 €

Cabbage is now approximated to be 15% more expensive at the supermarket than at the organic store. In this way, the mean value percentage markups of the missing foods could be calculated. This procedure is used in each case for the vegan and omnivorous shopping cart, as well as for all price categories.

Conventional tofu is the only conventional product, which was not available at the discounter. In this case, the supermarket price serves as comparative value, since there is no shopping cart from the organic store and, at the supermarket, all three price levels (cheap, medium, expansive) were available.

When using this methodology, the order of the three price levels may change in individual cases: The recalculation of the average value, which tends to be lower for a higher price category, can result in a calculated "expensive" price being cheaper than the calculated price in the lower price category. To correct this, the incorrect calculated prices are replaced with the mean calculated price value. More precisely, this means that a cheap price, that is more expensive than the mid-priced one, is replaced by the mid-priced one. The same applies to an expensive product that is cheaper than the other prices calculated.

Appendix B

Figure A1 shows the cumulative prices of all price levels for the respective shopping baskets. The organic prices of all shopping stores are on a similar price level. At the organic market, there are additional products from a higher price level, as can be seen from the high expensive prices. A conventional purchase from the middle price level at a discounter or a supermarket is about as expensive as a purchase with the cheapest organic products.

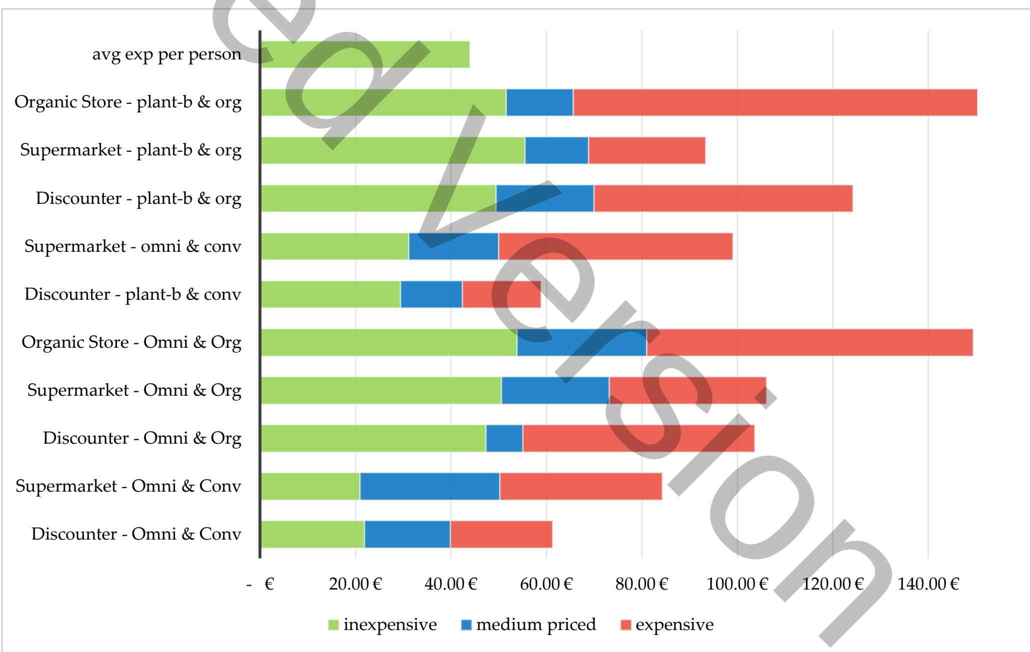

Figure A1. Cumulative prices of the 10 shopping baskets and the current average expenditure of one person.

Table A4. Detailed overview of all price categories including current issues. The blank lines occur due to the missing product categories in the individual shopping baskets.

Grocery Store		Organic Market		Supermarket				Discounter			
Production Practice	**Status Quo**	**Organic**		**Organic**		**Conventional**		**Organic**		**Conventional**	
Diet		**Omnivorous**	**Plant-Based**	**Omnivorous**	**Plant-Based**	**Omnivorous**	**Plant-Based**	**Omnivorous**	**Plant-Based**	**Omnivorous**	**Plant-Based**
Grain and Cereal Products	5.75 €	6.34 €	4.46 €	5.32 €	4.98 €	2.61 €	3.98 €	6.91 €	6.15 €	2.41 €	4.08 €
Vegetable and Pulses	4.60 €	8.65 €	12.14 €	11.19 €	15.89 €	4.61 €	5.59 €	11.10 €	14.01 €	5.63 €	6.93 €
Fruit and Nuts	4.14 €	5.76 €	11.16 €	5.69 €	11.10 €	2.95 €	5.76 €	4.03 €	10.69 €	3.09 €	6.03 €
Milk and Milk products and Egg	5.52 €	7.57 €	-	4.94 €	-	2.73 €	-	5.81 €	-	2.79 €	-
Mild and Milk products Alternative	-	-	6.84 €	-	5.11 €	-	6.21 €	-	5.77 €	-	5.48 €
Meat, Sausage and Fish	7.13 €	15.24 €	-	14.45 €	-	4.21 €	-	11.64 €	-	3.98 €	-
Fats	1.15 €	1.54 €	2.04 €	1.50 €	2.72 €	0.69 €	1.02 €	1.36 €	0.92 €	1.02 €	0.70 €
Beverage	4.37 €	8.76 €	8.77 €	7.50 €	7.91 €	3.18 €	3.18 €	6.49 €	6.69 €	2.97 €	2.97 €
Additional Food	1.84 €	-	6.19 €	-	7.83 €	-	5.41 €	-	5.26 €	-	3.25 €
Misc.	9.21	-	-	-	-	-	-	-	-	-	-

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Appendix B

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ARTICLE

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Calculation of external climate costs for food highlights inadequate pricing of animal products

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Although the agricultural sector is globally a main emitter of greenhouse gases, thorough economic analysis of environmental and social externalities has not yet been conducted. Available research assessing agricultural external costs lacks a differentiation between farming systems and food categories. A method addressing this scientific gap is established in this paper and applied in the context of Germany. Using life-cycle assessment and meta-analytical approaches, we calculate the external climate costs of foodstuff. Results show that external greenhouse gas costs are highest for conventional and organic animal-based products (2.41€/kg product; 146% and 71% surcharge on producer price level), followed by conventional dairy products (0.24€/kg product; 91% surcharge) and lowest for organic plant-based products (0.02€/kg product; 6% surcharge). The large difference of relative external climate costs between food categories as well as the absolute external climate costs of the agricultural sector imply the urgency for policy measures that close the gap between current market prices and the true costs of food.

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Social and environmental costs from the emission of greenhouse gases (GHGs) are currently not considered in the cost structure of farmers or the subsequent food chain[1,2], and are thus a burden on other market participants, future generations, and the natural environment. These external costs are not yet included in the market prices for food and, in the absence of current compensation payments, lead to significant market price distortions[3] and welfare losses for society as a whole[4,5]. In order to close the gap between the current market prices and the true costs of foodstuff, GHG emissions from agriculture have to be quantified and monetized. The United Nation's (UN) polluter-pays principle[6] implies that in order to compensate for externalities, external costs should be levied on the producer prices of food, or other economic policy measures should be taken to reduce or compensate harmful costs caused by food production[7].

There has been some scientific engagement previously, as Pretty et al.[8] set the scene for agricultural externality analysis at this century's beginning: they were able to record significant environmental impacts of agriculture at the overall societal level in monetary terms for the UK. This approach was translated for other regions subsequently, with calculations of agricultural external costs for the USA and Germany[2,9]. However, these first external cost assessments, with their characteristic top-down approaches, did not link specific causal emission values with said costs. Yet, a bottom-up approach for monetizing externalities of country-specific agricultural reactive nitrogen emissions was later developed[10] and subsequently used for an external cost assessment of Dutch pig production[11]. Despite, assessments concerning important agricultural emissions comprehensively differentiating between a variety of food categories are yet missing. There exists a range of studies that quantify food-category-specific GHG emissions[12–15] while other studies disclose the difference of climate effects from conventional and organic practices[16–28]. Monetizing such emissions, however, has been done for constituent food categories only[29]. An encompassing connection between the quantification and monetization of GHG emissions differentiated by food categories and farming systems is what seems to be lacking in the currently available literature.

Congruent to methodological differences for monetizing agricultural greenhouse gases, there are also differences in the estimation level of greenhouse gas costs. Prices per tonne of emission at the stock market, for example, are as low as 5.34 € on average during this study's reference year, whereas they were more than 10 € higher on average ten years prior and have risen up to about 25 € on average especially in the past two years[30]. The German Federal Environmental Agency's (UBA) suggestion for the damage costs of GHG emissions also rose within the last years: in 2010 they suggested a rate of 80 € per tonne of CO_2 equivalents (eq)[31], whereas this increased to 180 € per tonne in 2019[32]. This price factor is congruent with the IPCCs evaluation from 2014, which states a reasonable cost rate of 181 \$ per tonne of CO_2 equivalents, calculating to ~173.5 €/tCO_2 eq[33]. This implies that a scientific consensus has been reached over the past years, considering an adequate cost rate for GHG-related damage. Furthermore, the price is expected to rise in the future, whereby a cost rate of over \$400 per tonne might be necessary by mid-century[34].

The aim of this paper, by building on previous work, including our own earlier research efforts[35,36], is to provide a method for a differentiated quantification and monetization of GHG emissions of a variety of foodstuff and farming practices. We thereby illustrate the present price difference between current producer prices and true costs. The established framework is tested in the German context and is further applicable for other country contexts and different externalities: Life-cycle assessment (LCA) tools, such as the one used in this study (see the section "Input data for quantification") for quantifying emissions of the examined foodstuff, also offer the data for other externalities. Further, production quantities as well as producer prices are largely available for other regional contexts. Thereby applicability and transferability of the presented method of quantification and monetization are ensured.

LCA has developed as a commonly used tool for examining material and substance flows of diverse products. Its origins lie in the analysis of energy flows, but it is now commonly used to assess various processes[37]. In general, the LCA method examines environmental and social impacts that occur during the entire lifetime of a product and can involve a monetization of such impacts. This includes both impacts from production and impacts occurring during the usage phase of a product up to its disposal (or consumption), as well as all intermediate emissions[38].

Additional to the consideration of CO_2 emissions, all so-called CO_2 equivalents (methane, CH_4; nitrous oxide, N_2O) are considered in greenhouse gas-emission assessments of the current literature, as these gases not based on carbon still contribute to climate effects[39]. These gases each have a defined global warming potential (GWP). Especially during the production of animal-based foodstuff, livestock-related gases, such as methane or nitrous oxide, significantly contribute to the overall GHGs emitted[40].

CO_2 is produced in agriculture through microbial degradation (rotting) and the burning of plant waste. In addition, considerable amounts of CO_2 previously bound in soils are released into the atmosphere through agricultural processes[41]. Indirect CO_2 emissions from agricultural transport, heat generation, and emissions from the production of nitrogen fertilizers[42] are of quantitative relevance as well. CH_4 is produced during the composting or conversion of organic substances in oxygen-poor environments, i.e., mainly during the digestion of ruminant farm animals[41]. N_2O is produced in agriculture mainly due to direct emissions from agricultural soils, mostly caused by the over-application of nitrogen fertilizer, and indirect emissions from the production of such fertilizer[43].

Consequently, we develop a calculation of the monetary valuation of carbon footprints for foodstuff, resulting in food (category)-specific external costs. We differentiate between the categories of conventional and organic products as well as animal-, dairy, and plant-based products, but also narrower categories such as beef (animal-based), milk (dairy), or cereal (plant-based). Our analysis shows that external cost differences are especially large between food categories, whereby animal products are associated by far with the highest external costs, followed by dairy and plant-based products. In contrast to food categories, the influence of production methods on external climate costs is much smaller.

If the resulting costs are addressed by economic policies in line with common economic theory, they would enable agricultural externalities to be internalized according to the polluter-pays principle and at the same time strengthen sustainable consuming behavior. Pricing of food that includes environmental and social costs would thus also significantly contribute to fair market conditions, and simultaneously to climate change mitigation.

Results

Outline. The quantification and monetization of externalities from agricultural GHG emissions for Germany is derived in the following. First, the input data are displayed. Second, these data are applied to our methodology (cf. "Method and data" section). Lastly, the output data are derived.

Quantification. Using the input data for quantification (for definition and origin refer to the section "Input data for quantification") as starting points, this subsection shows results of the emissions data for food categories at different aggregation levels. All foodstuffs are divided into plant-based, animal-based, or dairy products classified as broad categories. The narrow categories are more fine-grained and divide plant-based foods into vegetables, fruits, cereals, root crops, legumes and oilseed, and animal-based foods into eggs, poultry, ruminants, and pork. Only milk is considered within the dairy products, as processing steps beyond the farmgate would be necessary to achieve other dairy products, such as cheese or butter. This, however, does not fall into the defined system's boundaries, which we chose as cradle to farmgate (cf. "Method and data").

The food-specific conventional emission data $g_{b,n,i,conv}$ is derived from the material-flow analysis tool GEMIS (Global Emission Modell of Integrated Systems)[44] and is the basis for calculating external costs. However, land-use-change-emissions (LUC) are not included in this dataset. Thus, we calculate these emissions ourselves, following the methodology of Ponsioen and Blonk[45] (see the section "Input data for quantification" for a detailed description) for the food-specific, narrow as well as broad categories, but only for conventional production. This is because LUC emissions almost entirely originate from the cultivation of imported crops, from countries where arable land is expanding at the cost of natural land. Only in conventional production, it is unreservedly allowed to import crops (as fodder) from locations outside of the regional context. This is in contrast to organic production where the majority of the fodder must come from farms from the same or directly neighboring federal states[46]. As LUC emissions do currently not arise within Germany (total area of arable land is decreasing)[47], it can be assumed that LUC emissions of organic production (in Germany) are of negligible scope (for details, refer to the section "Method and data").

In order to derive emission data for organic production, the conventional emission data (excluding LUC emissions) is differentiated according to the method described in the "Method and data" subsection on output data resulting in the values shown in the columns for organic production in Table 1.

The results of this differentiation of the GEMIS data are laid out in Table 2, where the emission difference between both systems is calculated for each of the three broad categories (plant-based, animal-based, dairy).

As can be seen in Table 2, the choice of the farming system has the largest effects in the production of animal-based foodstuff. In this category, organic production causes 150% of emissions from conventional production. It is important to note that emissions from LUC are not yet included in the underlying data and calculation, which when considered changes the results for animal-based foodstuff drastically (compare column conv with LUC in Table 1). In the two other broad categories, organic causes fewer emissions than conventional production. Organic plant-based products cause 57% and dairy products 96% of emissions from conventional products. Explanations for these differences are elaborated in the "Discussion".

We aggregate GEMIS emission data ($q_{b,n,i,conv}$) to narrow ($e_{b,n,conv}$) and broad categories ($E_{b,conv}$) by multiplying the respective emission data with the quantitative production shares of food-specific products in narrow categories and the shares of narrow in broad categories (cf. "Input data for quantification"). From these aggregated conventional emission values, we derive emissions for organic production. For narrow as well as broad categories, the respective conventional emission values are multiplied with the applicable emission differences $D_{b,org/conv}$ (see Table 2). The results are illustrated in Table 1.

Examining the broad categories in the left columns of Table 1, it can be seen that animal-based products cause the highest emissions per kilogram of product at 13.38–13.39, followed by dairy at 1.05–1.33 and plant-based products with 0.11–0.20 kgCO_2eq/kg product. Within narrow categories, ruminants cause by far the highest emissions with 36.95–37.37 over all products while legumes cause the lowest emissions with only 0.02–0.03 kg CO_2eq/kg product. As follows from Table 2, with LUC emissions included, organically produced food causes fewer emissions in the broad plant-based and dairy categories, while causing slightly higher emissions in the animal category. In the narrow categories, organic production performs worse for eggs, poultry, and ruminants. Explanations for emission differences between the different food categories and the production methods will be addressed in the "Discussion".

Monetization. When putting the calculated emission values into monetary units with the emission cost rate from the German Federal Environment Agency (UBA) of 180 € per ton of CO_2 equivalents[32,33], their absolute external costs can be derived. The results are shown in Table 3 for conventional and organic farming in columns $C_{b,conv}$ and $C_{b,n,conv}$ as well as $C_{b,org}$ and $C_{b,n,org}$, respectively. When

Table 1 Emission data for food-specific, narrow and broad categories (following the classification from the German Federal Office of statistics[88]).

Emission data (in kg CO_2eq/kg product)

Broad categories [*b*]	Prod. method			Narrow categories [*n*]	Prod. method			Food-specific [*i*]	Prod. method		
	Conv. [$E_{b,conv}$]	With LUC	Org. [$E_{b,org}$]		Conv. [$e_{b,n,conv}$]	With LUC	Org. [$e_{b,n,conv}$]		Conv. [$g_{b,n,i,conv}$]	With LUC	Org. [$g_{b,n,i,org}$]
Plant-based	0.20	/	0.11	Vegetables	0.04	/	0.02	Field Vegetables	0.03	/	0.02
								Tomatoes	0.39	/	0.22
				Fruit	0.25	/	0.14	Fruit	0.25	/	0.14
				Cereal	0.36	/	0.21	Rye	0.22	/	0.13
								Wheat	0.38	/	0.21
								Oat	0.36	/	0.21
								Barley	0.33	/	0.19
				Root Crops	0.06	/	0.04	Potatoes	0.06	/	0.04
				Legumes	0.03	/	0.02	Beans	0.03	/	0.02
				Oilseed	1.02	/	0.58	Rapeseed	1.02	/	0.58
Animal-based	8.90	(13.38)	13.39	Eggs	1.17	(1.18)	1.76	Eggs	1.17	(1.18)	1.76
				Poultry	13.16	(15.81)	19.80	Broilers	13.16	(15.81)	19.80
				Ruminants	24.84	(36.95)	37.37	Beef	24.84	(36.95)	37.37
				Pork	5.54	(9.56)	8.34	Pork	5.54	(9.56)	8.34
Dairy	1.09	(1.33)	1.05	Milk	1.09	(1.33)	1.05	Milk	1.09	(1.33)	1.05

Food-specific emission data for conventional production was derived from Global Emissions Model for Integrated Systems (GEMIS)[44] and aggregated to narrow and broad categories with German production data[88]; differentiation between conventional and organic production was derived with a meta-analytical approach (for details refer to the "Method and data" section and Supplementary Note 1 and Table 1); land-use change (LUC) data are approximated to be the LUC emissions of soymeal fodder, emissions of it are calculated with the method of Ponsioen and Blonk[45].
Emission data including LUC emissions are shown in brackets. Source data are provided as a source data file.

Table 2 Determining the emission difference ($D_{org/conv}$) between organic and conventional production in different countries' contexts through the application of meta-analytical methods.

Name	Country	Produce	$D_{org/conv}$	Relevance PY	CY	SJR	SUM	WEIGHT
Plant-based								
Aguilera et al. (2015a)[16]	Spain	citrus, fruits	49%	10	3	10	23	26%
Aguilera et al. (2015b)[17]	Spain	cereals, legumes, veg.	45%	10	3	10	23	26%
Cooper et al. (2011)[18]	UK	crop rotation (no differentiated values for specific crops given)	42%	8	2	2	12	13%
Küstermann et al. (2008)[19]	Germany	arable (no specific crop differentiation/rotation described)	72%	7	3	4	14	16%
Reitmayr (1995)[20]	Germany	wheat, potatoe	63%	0	1	1	2	2%
Tuomisto et al. (2012) [21]	EU	arable (no specific crop differentiation/rotation described)	36%	9	2	5	16	18%
			49%	x 117%			*90*	*100%*
			57%					
Animal-based								
Basset-Mens; Werft (2005)[22]	France	pig	95%	5	7	6	18	35%
Casey; Holden (2006) [23]	Ireland	beef	82%	6	3	10	19	37%
Flessa et al. (2002)[24]	Germany	beef/cattle	73%	4	5	6	15	29%
			84%	x 179%			*52*	*100%*
			150%					
Dairy								
Bos et al. (2014)[25]	Netherlands	dairy	61%	10	3	4	17	24%
Dalgaard et al. (2006)[26]	Denmark	dairy	57%	6	2	6	14	20%
Haas et al. (2001)[27]	Germany	dairy	67%	3	8	5	16	23%
Thomassen et al. (2008)[28]	Netherlands	dairy	65%	7	10	6	23	33%
			63%	x 152%			*70*	*100%*
			96%					

Arrows represent the yield/productivity difference for each category; this difference is then multiplied with the emission difference per ha to derive the emission difference per kg (in bold). PY = publishing year, CY = yearly citations, SJR = SciMago journal ranking, SUM = sum of all three factors, WEIGHT = weighted sums of category.
A more detailed explanation of the studies' specifics including the weighting scheme can be found in the Supplementary Note 1 and Table 1. Source data are provided as a source data file.

these external costs are assessed in relation to their corresponding producer price (pp), the resulting percentage surcharge (Δ) reflects the price increase necessary to internalize the GHG-related externalities arising from food production. Relative results for conventional and organic farming are shown in column $\Delta_{b,conv}$ and $\Delta_{b,n,conv}$ as well as $\Delta_{b,org}$ and $\Delta_{b,n,org}$, respectively. Food-specific products (see Table 1) are omitted in this table since their respective monetary costs and percentage price increases follow the same pattern as the narrow category. Please refer to the "Method and data" section for details of the full calculation methodology and data origin.

For the broad category, the results are visualized in Figs. 1 and 2, where Fig. 1 shows the absolute price increases (in Euro), whereas Fig. 2 shows the relative price increases (in percent).

Following, we explain the broad categories' data further. The narrow categories follow the same narrative overall. Looking at Table 4 and Fig. 1, the external costs of organic plant-based products are clearly the lowest (0.02€/kg product). External costs for conventional plant-based products are about twice as high (0.04€/kg product), although still relatively low compared with the other two broad categories. This shows that even the animal-

Table 3 Producer prices (pp), external costs (C) and percentage price increases (Δ) for narrow and broad food categories when externalities resulting from greenhouse gas emissions are monetized.

Broad categories [b]	Prod. method						Narrow categories [n]	Prod. method					
	Conv.			Org.				Conv.			Org.		
	$pp_{b,conv}$ (€/kg Prod)	$C_{b,conv}$ (€/kg Prod) with LUC	$\Delta_{b,conv}$ with LUC	$pp_{b,conv}$ (€/kg Prod)	$C_{b,org}$ (€/kg Prod)	$\Delta_{b,org}$		$pp_{b,n,conv}$ (€/kg Prod)	$C_{b,n,conv}$ (€/kg Prod) with LUC	$\Delta_{b,n,conv}$ with LUC	$pp_{b,n,org}$ (€/kg Prod)	$C_{b,n,org}$ (€/kg Prod)	$\Delta_{b,n,org}$
Plant-based	0.14	0.04	25%	0.36	0.02	6%	Vegetables	0.69	0.01	1%	1.10	~0.00	~0%
							Fruit	0.50	0.05	9%	0.57	0.03	5%
							Cereal	0.09	0.07	72%	0.31	0.04	12%
							Root Crops	0.08	0.01	14%	0.30	0.01	2%
							Legumes	0.02	0.01	33%	0.13	~0.00	3%
							Oilseed	0.37	0.18	50%	0.42	0.10	25%
Animal-based	1.66	1.60 *(2.41)*	97% *(146%)*	3.41	2.41	71%	Eggs	1.21	0.21 *(0,21)*	17% *(18%)*	3.42	0.32	9%
							Poultry	1.72	2.37 *(2,85)*	138% *(165%)*	2.31	3.56	154%
							Ruminants	3.38	4.47 *(6,65)*	132% *(197%)*	3.90	6.73	173%
							Pork	1.35	1.00 *(1,72)*	74% *(128%)*	3.61	1.50	42%
Milk	0.26	0.20 *(0.24)*	75% *(91%)*	0.48	0.19	40%	Milk	0.26	0.20 *(0,24)*	75% *(91%)*	0.48	0.19	40%

Producer prices are calculated by dividing the total amount of producer proceeds for each category (in Euro)[99] with its total production quantity[88,89]; external costs are derived by multiplying emission values from Table 1 with the emission cost rate of 180 €/tCO_2eq; percentage price increases are the ratio of external costs to producer prices; in brackets are the values with land-use change (LUC) emission costs included.
In each broad and narrow category, the highest external costs and percentage surcharge are highlighted in red and the lowest in green. Source data are provided as a source data file.

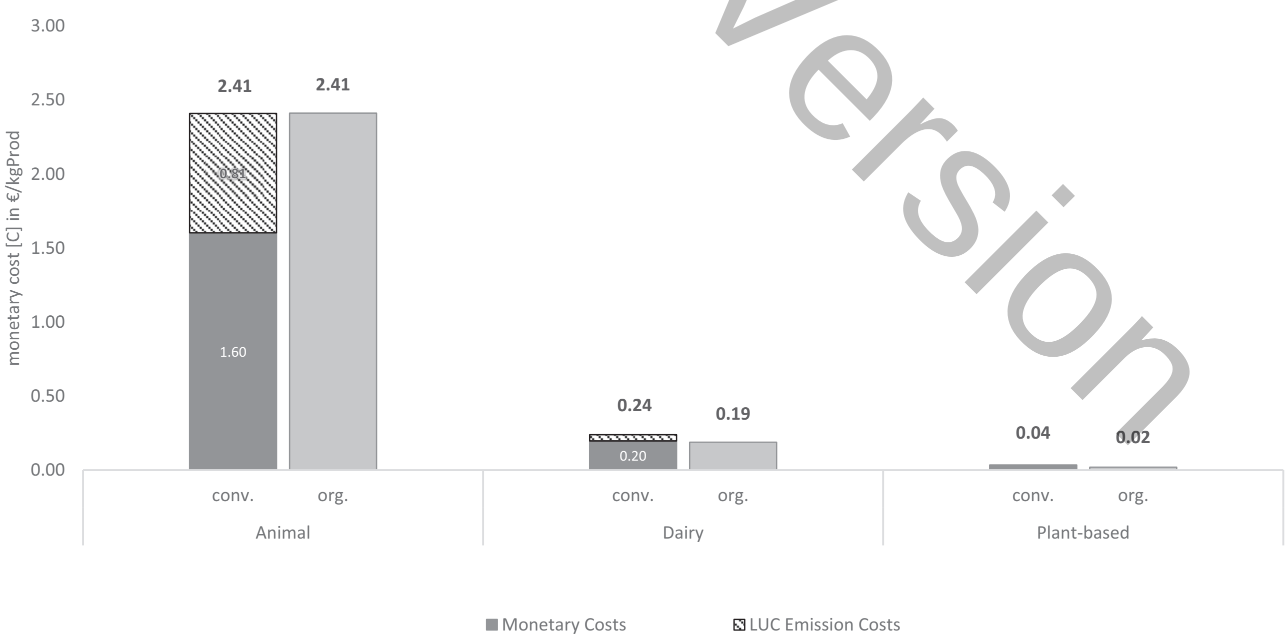

Fig. 1 Visualization of monetary costs for broad food categories. Monetary costs [C] for broad categories (animal-based, dairy, plant-based in the comparison between conventional and organic production) arising from monetized externalities of greenhouse gas emissions. For conventional production (animal-based and dairy), the external costs from land-use change (LUC) emissions are highlighted separately. Source data are provided as a source data file.

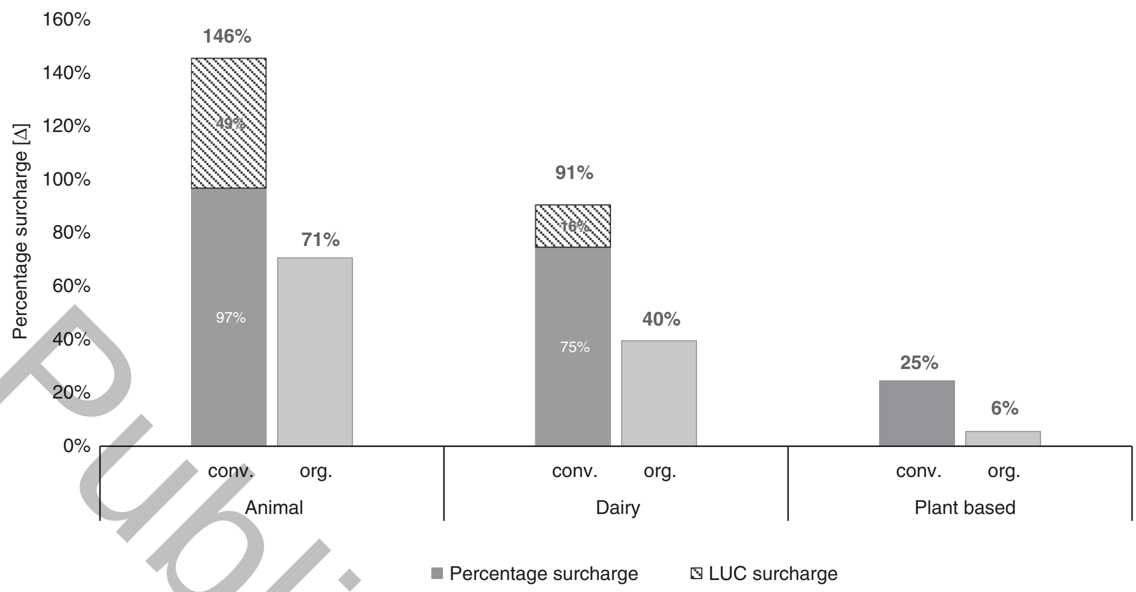

Fig. 2 Visualization of percentage price increases for broad food categories. Relative percentage price [Δ] increases for broad categories (animal-based, dairy, plant-based in the comparison between conventional and organic production) when externalities of greenhouse gas emissions are included in the producer's price. For conventional production (animal-based and dairy), the surcharge from land-use change (LUC) emissions is highlighted separately. Source data are provided as a source data file.

Table 4 Production data [$q_{b,n,i,conv}$] for food-specific products and share in broad and narrow categories for 2016 in Germany.

Production data

Broad categories [b]	Share in broad categories	Narrow categories [n]	Share in narrow categories	Food-specific [i]	Total production quantity (in 1000 t) [$q_{b,n,i,conv}$]
Plant-based	7%	Vegetables	98%	Field vegetables	3166
			2%	Tomatoes	78
				Other	63
	2%	Fruit	100%	Fruit	1183
				Other	0
	33%	Cereal	5%	Rye	733
			82%	Wheat	13,026
			1%	Oat	101
			13%	Barley	2080
				Other	0
	54%	Root Crops	100%	Potatoes	8577
				Other	17,800
	1%	Legumes	100%	Beans	148
				Other	280
	3%	Oilseed	100%	Rapeseed	1595
				Other	61
Animal based	8%	Eggs	100%	Eggs	716
				Other	0
	17%	Poultry	100%	Broilers	1510
				Other	0
	13%	Ruminants	100%	Beef	1098
				Other	18
	62%	Pork	100%	Pork	5559
				Other	0
Dairy	100%	Milk	100%	Milk	31,736
				Other	0

Production data were obtained from the German Federal Office of Statistics[88] and AMI[89,90].
Source data are provided as a source data file.

based product emitting the lowest rate of GHG within its broad category causes higher external costs than the plant-based product emitting the highest rate of GHG emissions within its broad category. Animal-based products cause the highest external costs (2.41 €/kg product), which are 10 times higher than dairy costs and 68.5 times higher than plant-based costs. Here, conventional farming (2.41 €/kg product) perform as well as organic farming (2.41 €/kg product). In all other broad categories, organic farming outperforms conventional farming. This advantage of organic farming is considerable as it produces 21% less emissions for dairy and 43% less emissions for plant-based products on average per kg.

However, the choice of the farming system shows a much stronger effect when it comes to percentage surcharges (Table 3 and Fig. 2). This is due to the fact that the producer price of organic food is consistently higher compared to conventional food. Absolute external costs lead to a less significant percentage price increase for organic products emphasizing the difference between these two production types. Conventional animal-based products would require the highest relative percentage price increase (146%), whereas organic plant-based products would require the lowest (6%) of all broad categories.

Discussion

In the following, the emission differences between food categories and production methods as well as the internalization of external costs itself will be discussed.

As the results show, the production of animal-based products —especially of meat—causes the highest emissions. These results are in line with the prevailing scientific literature[12–15,48]. Such high emissions stem from the resource intensive production of meat, because of an inefficient conversion of feed to animal-based products. For beef cattle, this conversion ratio is reported by Pimentel and Pimentel to be as high as 43:1, meaning that 43 kg of feed are needed to produce 1 kg of beef product. These ratios differ significantly within meat categories, with broilers having the lowest ratio of all meat with only 2.3:1[49]. Furthermore, emissions from the animal itself through manure and digestion, as well as heating of stables, are also relevant factors which contribute to the high emissions of animal-based products. Secondary animal-based products, such as milk and eggs, however, cause lower emissions than meat. Again, these findings are in line with other sources[15,50]. This can be derived from the fact that the mass of milk or eggs a farm animal produces during its life is significantly higher than its own body weight on the day of slaughter. Thus, the same amount of resource input leads to a significantly higher amount of secondary (eggs, milk, etc.) than primary (meat) animal-based products. Hence, emissions from these resource inputs have a far smaller weight in secondary animal-based products.

Looking at the emission differences between conventional and organic production, the lower emissions of organic products in all three broad categories can be explained by the stricter rules under which organic farming is practiced. The EU-Eco regulation (2013) prohibits the use of mineral nitrogen fertilizers on organic farms. Therefore, direct emissions from the soil on which the fertilizer is used, and indirect emissions due to fertilizer production are lower compared to conventional production. Although the question to which extent animal manure causes less N_2O emissions than nitrogen fertilizers in the form of direct soil emissions is controversial[51], a more careful nutrient handling on organic farms poses further explanation as to why considerable direct N_2O emissions are avoided on said farms[52]. With regard to the feeding of animals (emissions of which are always allocated to the respective animal-based products in this study; cf. "Method and data" subsection on input data) on an organic farm, Article 14d of the EU-Eco regulation stipulates that only organic feed—mainly produced on the local farm (or other organic farms from the same region)—may be used. As our results in the subsection on quantification show, organically produced plants emit less GHG compared to their conventional counterparts. This notion can also be translated for the production of fodder plants. GHG emissions are thus saved by the more climate-friendly cultivation of organic fodder. Longer transport routes are also avoided as organic practice largely prohibits the use of imported fodder, which in the case of conventional agriculture in Germany includes rapeseed meal and maize from mostly Russia and Ukraine as well as soy from Brazil and Argentina. The cultivation of soy in these countries is associated with significant LUC emissions, which consequently are not applicable to organic products. The feed of organic dairy cows incorporates a significantly higher proportion of grazing (29.5% compared to 5.0%), which also avoids GHG emissions associated with the production of industrial feed for conventional dairy cows[53]. Moreover, the use of grassland instead of farmland leads to the preservation of CO_2 sinks[54]. However, the difference between farming practices is lower in both primary, and secondary animal-based products compared to the difference in plant farming. This may be explained with the higher use of land due to organic regulations prescribing a certain amount of land per animal, which is higher compared to average conventional production[22–24], as well as a higher living age and lower productivity of organically produced feed and raised animals[53] (cf. Table 2). This counterbalances or even reverses the described positive aspects of organic animal farming. Latter is the case for the narrow categories eggs, poultry as well as ruminants, for which organic farming results in higher emissions. For pork, however, organic farming achieves lower emissions. Such divergence of the ratio between farming system's emissions inside the animal-based category is explained by the different input quantities of soymeal (and the associated LUC emissions) into each product. As LUC emissions constitute a large share of the total emissions of a conventional animal-based product, the disbenefit of conventional products mainly depends on how large this share is. As this share is highest for pork (72%), it is the only subcategory of animal-based products, where organic farming results in lower emissions per kg. However, as the emissions of pork and their external costs are weighted the strongest inside the animal-based category (due to their high production quantity), the emission advantage of organic farming is passed on to the results for the broad category of animal-based products.

Further doubt toward a transition to organic farming was spread by Smith et al.[55], who rightfully addressed the potential increase of emissions resulting from a complete transition from conventional toward organic farming, given consumption patterns stay the same. These increases are thought to result from a higher amount of imported food, due to lower (regional) yields from organic farming. The financial incentives of internalization presented in our paper and the associated changing consumption patterns, however, pose a solution to these identified problems. Due to price elasticities of demand for food products (which are consistently regarded as normal goods in economic literature), appropriate pricing of food would make products of organic production more competitive compared to their conventional counterparts[56]: customers would increasingly opt for organic foodstuff due to the lowered price-gap between the two options. Although organic products are not always associated with lower emissions than conventional products (in the case of eggs, poultry, and ruminants), percentage price increases of organic products are consistently lower than for conventional products. Correspondingly, decreases in demand are lower for organic products. Thus, there would be a consistent advantage for organic products along with all products categories. This could potentially press the boundaries of land use for agriculture as organic practices mostly require more land than conventional systems due to lower yields[57–59]. However, our results suggest an increase in the prices of animal-based products to a significantly larger extent than the prices of plant-based products. The presumed consequential decline of animal-based product consumption would free an enormous landmass currently used for feed production. Further expansion of area-intensive organic agriculture would subsequently be made possible[60]. Furthermore, there is evidence that a shift from conventional to organic practices would indeed be beneficial for the ecosystem services and long-term efficiency provided by the particular land area[1,61]. If one takes into account the temporal change in yield difference which would result by converting farms from conventional to organic farming, there is scientific consensus that the yield gap will decrease over time[62,63]. Comparative studies between different cultivation methods also show that organic farming has lower soil-borne GHG emissions and higher rates of carbon sequestration in the soil[52,64]. Soil degradation resulting from conventional systems would slow down or could even be reversed by changing to organic farming[19,65].

The internalization of external costs would also likely result in a lowered amount of thrown away food as appreciation for food would rise with its increased monetary value[66]. Thereby, further positive effects on efficiency and the environmental burden of food production would be achieved. Furthermore, a change in demand toward low-carbon (organic plant-based) food products is shown by Springmann et al. to positively affect the well-being and health of the individual, whereby national spending in health care could be reduced[67].

Price surcharges for externalities might be perceived as an additional financial burden for consumers[68]. It must be considered, however, that the costs of today's agricultural externalities are paid for by society and thus also by the individual already. This is yet done indirectly, for example, through emergency aid payments for floods or droughts and other increasing extreme weather conditions as an effect of global warming. When external costs are internalized, however, it would be possible for these external costs to be paid according to the polluter-pays principle[6] and thereby in an arguably fairer way. Following this principle, consumers demanding environmentally detrimental foodstuff would directly pay for its damages, whereas environmentally conscious consumers not wishing to support unsustainable farming practices are not financially burdened with its implications.

There is an opportunity to avoid or mitigate future damage by using additional government revenues resulting from the internalization of external climate costs: a subsidy policy providing greater incentives for sustainable agriculture at the farm level could be established. This could be done by ensuring that all received money from internalization is redistributed. Redistribution, which is the responsibility of national and international economic policy, should be carried out in particular for the benefit of the farmers concerned and should incentivize them to reduce their environmental impact. At the same time, social compensation appears to be necessary in order to help economically disadvantaged citizens, who are spending a far higher proportion of their income on food than economically more privileged groups. Surely, there are many political controversies implied in internalization policies. A thorough discussion of them, however, shall not be elaborated here in greater detail, since this paper's main focus is to deliver the quantitative basis for such political discourse.

This paper laid out a method to calculate product-specific external costs in the context of GHG emissions for foodstuff from German agricultural production. There is wide-ranging applicability of the method presented here. It can, for example, be used to assess the costs of further externalities, as databases such as the used GEMIS offer further data (such as externalities concerning nitrogen discharge or energy consumption), not only for Germany but also other regional contexts. We present many entry points from which to draw upon and add to the evolving literature on the true costs of food. Furthermore, a concern for current LCA methods, and thus a highly relevant research area, is the question of how to implement LUC emissions on a product-specific level. Since the focus of this study is on German production, LUC emissions are of negligible proportion for locally grown products, as agricultural land area is slightly decreasing in Germany[55]. For animal-based products, however, a significant amount of emissions arise due to additional LUC emissions from feed imports. We calculate such emissions with the method of Ponsioen and Blonk[45], whereby the shortcomings of common direct and indirect LUC assessment are largely prevented, and emissions are calculated on the basis of available statistical land-use data for a specific country. However, as there currently are different scientific approaches to LUC assessment, we list LUC emissions separately from other types of emissions. The here analyzed stage of agricultural production, assessed within the system boundaries of cradle to farmgate, causes the greatest externalities along the value chain of foodstuff[69]. Despite this, further research should also be conducted for the activities succeeding the farmgate (e.g., processing and logistics) and corresponding externalities.

The approach presented here represents a contribution to the true costs of food, which—even with partial implementation—could lead to an increase in the welfare of society as a whole by reducing current market imperfections and their resulting negative ecological and social impacts.

Methods

Outline. In this section, first, we outline the method as a whole to give the reader an orientation and context for the following two parts. Second, we discuss the input data (for quantification and monetization). Third, we explain the merging of all input data, and thus the calculation of the output data. Finally, we address the influence of uncertainties on our method. The reference year for this analysis is 2016, and the reference country is Germany, which is listed as the third most affected country in the Global Climate Risk Index 2020 Ranking[70].

Method in short. We differentiate between two steps within this method of calculating food-category-specific externalities and the resulting external costs. These are first the quantification and second the monetization of externalities from GHGs (visualized in Fig. 3). We use this bottom-up approach following the example of Grinsven et al.[10], who conducted a cost-benefit analysis of reactive nitrogen emissions from the agricultural sector. This two-stepped method also allows the adequately differentiated assessment for GHG emissions of various food categories.

The quantification includes the determination of food-specific GHG emissions —also known as carbon footprints[39]—occurring from cradle to farmgate by the usage of a material-flow analysis tool. Carbon footprints are understood within this paper in line with Pandey et al.[71] where all climate-relevant gases, which (in addition to CO_2) include methane (CH_4) and nitrous oxide (N_2O), are considered. Their 100-year CO_2 equivalents conversion factors are henceforth defined as 28 and 265, respectively[72]. Here, the material-flow analysis tool GEMIS (Global Emission model for Integrated Systems)[44] is used, which offers data for a variety of conventionally farmed foodstuff. As GEMIS data focus on emissions from conventional agricultural systems, we carried out the distinction to organic systems ourselves. We determined the difference in GHG emissions between the systems by applying meta-analytical methods to studies comparing the systems' GHG emissions directly to one another. Meta-analysis is commonly used in the agricultural context, for example, when comparing the productivity of both systems[57–59] or their performance[1].

For better communicability, we first aggregate the 11 food-specific datasets given in GEMIS to the broader food categories plant-based, animal-based, and dairy by weighting them with their German production quantities (cf. "Results" subsection on quantification). On top of that, LUC emissions are calculated for conventional foodstuff.

Through monetization, these emission data are translated into monetary values, which constitute the category-specific external costs. The ratio of external costs to the foodstuff's producer price represents the percentage which would have to be added on top of the current food price to internalize externalities from GHGs and depict the true value of the examined foodstuff.

Input data for quantification. Starting with the data on food-specific emissions, GEMIS is used because of its large database of life-cycle data on agricultural products with a geographic focus on Germany. GEMIS is a World-Bank acknowledged tool for their platform on climate-smart planning and drew on 671

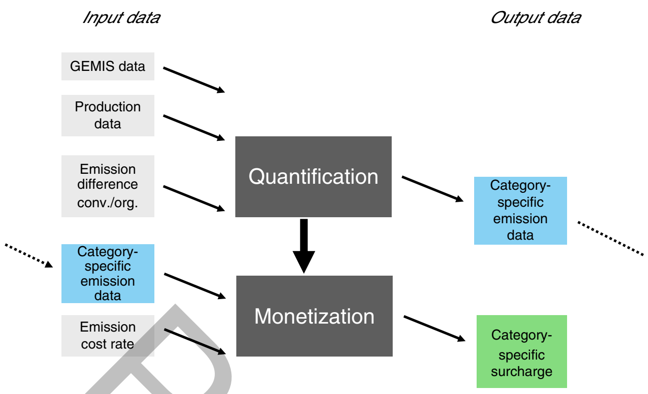

Fig. 3 Visualization of the method. The method includes quantifying and monetizing product-specific externalities. In the case of Germany, emission data were obtained from the Global Emission Model for Integrated Systems (GEMIS)[44]. We used production data from the German Federal Statistical Office[88] and AMI[89,90], and calculated the emission difference between organic and conventional production based on a meta-analytical approach (see “Results” subsection on input data for quantification). The category-specific emission data were calculated on the basis of these input data. The emission cost rate was obtained from the German Federal Environmental Agency (UBA)[32]. The category-specific external costs were determined on the basis of the previously developed price-quantity-framework (see “Results” subsection on input data for monetization).

references, which are traced back to 13 different databases. The German Federal Environmental Agency uses GEMIS as a database for their projects and reports establishing it to be an adequate tool for the German context especially[73,74]. This tool is provided by the International Institute for Sustainability Analysis and Strategy (IINAS). GEMIS offers a complete view on the life cycle of a product, from primary energy and resource extraction to the construction and usage of facilities and transport systems. As GEMIS only offers data for the year 2010, we conducted a linear regression on the basis of the prevailing emission trend for the German agricultural context in order to align the data with the reference year 2016[75]. For this, annual German emission data from 2000 to 2015 from the Federal Environmental Agency of Germany was used[76]. On every level of the process chain, data on energy- and material-input, as well as data on output of waste material and emissions, are provided by GEMIS. These data consist partly of self-compiled data from IINAS and partly of data from third-party academic research or other life-cycle assessment tools. Specific information on the data sources is available for every dataset of a product. In this study, the system boundaries for assessing food-specific GHG emissions span from cradle to farmgate. This means that we consider all resource inputs and outputs during production up to the point of selling by the primary producer (farmgate). This includes emissions from all production-relevant transports as well as emissions linked to the preliminary building of production-relevant infrastructure.

We specify that for animal-based products, emissions from feed production, as a necessary resource input, are assigned to these animal-based products. Such emissions naturally should include LUC emissions. LUC emissions are of negligible proportion for locally grown products, as agricultural land area is slightly decreasing in Germany[47]. Thus, we have to focus solely on imported feed for conventional animal-based and dairy products. Organic feed is not considered as article 14d of the EU-Eco regulation stipulates that organic farms have to primarily use feed which they produce themselves or which was produced from other organic farms in the same region[77]. The region is understood as the same or the directly neighboring federal state[46]. Although the EU-Eco regulation does not completely rule out fodder imports from foreign countries, it limits its application significantly. Also, one has to consider that over 60% of the organic agricultural area belongs to organic farming associations[78]. These associations stipulate even stricter rules than the standard EU-eco regulation. Examples are Bioland, where imports from other EU and third countries are only allowed as a time-limited exception[79], Naturland, where additionally imports of soy are banned completely[80], or Neuland, that ban any fodder imports from overseas[81]. We thus assume that the emissions that could possibly be caused by organic farming in Germany through the import of feed constitute a negligibly small fraction of the total emissions of a product. Thus, we follow common assumptions from the literature[82–84] and calculate no LUC emissions for organic products. For conventional products, we calculate LUC emissions by application of the method of Ponsioen and Blonk[45]. This method allows the calculation of LUC emissions for a specific crop in a specific country for a specific year. With regards to the year, we apply our reference year 2016. With regards to crop and country one has to keep in mind that in the case of Germany, the net imports of feed are the highest for soymeal, followed by maize and rapeseed meal, making up over 90% of all net positive feed imports[85]. Maize and rapeseed meal are both imported mainly from Russia and Ukraine (93% and 87% of all imports[86]). Taken together, the crop area of Russia and Ukraine is decreasing by 150,000 ha/year (data from 1990 to 2015 were used[87]). Following Ponsioen and Blonk[45], we thus assume that there are no LUC emissions of agricultural products from these countries. This leaves us with soymeal, of which 97% are imported from Argentina and Brazil. We thus calculate LUC emissions of soymeal for Argentina and Brazil, respectively. Data are used from Ponsioen and Blonk[45], except for the data of the crop area, where updated data from FAOSTAT are used in order to match the reference year. We then weigh those country-specific emission values according to their import quantity. This results in 2.54 kg CO_2eq/kg soymeal. To incorporate this value into the conventional emission data from GEMIS, we map the LUC emissions to all the soymeal inputs connected to the food-specific products.

For aggregation to narrow categories, we categorize every dataset from GEMIS into one of the eleven narrow food categories. The choice of separation into these specific categories is based on the categorization of the German Federal Office of Statistics[88] from which production data were obtained. According to one category’s yearly production quantity, we incorporate every food product into the weighted mean of its corresponding food category. Thus, the higher a food’s production quantity, the greater the weight of this product’s emission data in the broad category’s emission mean. All data on the production quantities refer to food produced in Germany in the year 2016. For this weighting and aggregation step, only production quantities used for human nutrition were considered, thus feed and industry usage of food are ruled out (in contrast to emission calculation, where feed is indeed considered). Besides the German Federal Office of Statistics[88], the source for this data is the German Society for Information on the Agricultural Market (AMI)[89,90]. Only production data for conventional production is used. Thereby, we imply ratios of production quantities across the food categories for organic production that are equal to those of conventional production. This does not fully reflect the current situation of organic production properties but allows for a fair comparison between the emission data of organic and conventional food categories. Doing otherwise would create ratios between emission values of organic and conventional broad categories that would not be representative of the ratios between organic and conventional narrow categories. In Table 4, all production data are listed, whereby total production quantities in 1000 t can be found in the right column. Translating these into percentage shares, the column right to the narrow category’s column represents the shares of the specific foods inside the narrow categories, whereas the column right to the broad category’s column represents the shares of the narrow categories inside the broad categories. These shares are expressed in formula 2a and 2b (see “Method and data” subsection on output data) by the terms $\frac{p_{b,n,conv}}{P_{b,conv}}$ (share in broad categories) and $\frac{q_{b,n,i,conv}}{p_{b,n,conv}}$ (share in narrow categories).

We aggregate GEMIS emission data ($q_{b,n,i,conv}$) to narrow ($e_{b,n,conv}$) and broad categories ($E_{b,conv}$) by multiplying the respective emission data with the shares from Table 3 (cf. formula 2a and b, “Method and data“ subsection on output data). From these conventional emission values, we derive emissions for organic production. For narrow as well as broad categories, the respective conventional emission values are multiplied with the applicable emission differences $D_{b,org/conv}$ (cf. Table 2).

With these data, we aggregate the above mentioned eleven food categories to three broad categories: plant-based, animal-based, and dairy. Besides the obvious differentiation between animal- and plant-based products, dairy is considered separately from other animal-based products because of its relatively high production volume and its, in contrast to that, relatively low externalities. Because the weighted mean of the three main categories is affected by the production quantities of its corresponding subcategories, mapping dairy into the animal-based category would otherwise distort the emission data of this very category.

As outlined before, only data regarding externalities of conventional agricultural production are included in GEMIS and could therefore be aggregated. Nevertheless, by applying meta-analytical methods regarding the percentage difference of GHG emissions between conventional and organic production, we derive the emission data for organic production for each of the broad categories (plant-based, animal-based, and dairy). It has to be noted that LUC emissions are consistently excluded at this level of calculation. To derive emission differences between organic and conventional farming, research was conducted by snowball sampling from already existing and thematically fitting meta-analysis, by keyword searching in research databases, as well as forward and backward search on the basis of already-known sources. Criteria for selected studies were climatic and regulative comparability to Germany. In the selected studies, relative externalities between conventional and organic farming are compared in relation to the cropland. To cover a reasonably relevant period, we decided to search for studies published within the past 50 years (from 1969 to 2018) and could therefore identify fifteen relevant studies, spanning from 1995 to 2015. Four of these studies have Germany as their reference country while the other eleven focus on other European countries (Denmark, France, Ireland, Netherlands, Spain, UK; please consult Table 2 for specifics). The weighted mean of the individual study results amounts to the difference in GHG emissions between the two farming production systems. As the selected studies are based on geophysical measurements and not on inferential statistics, a weighting based on the standard error of the primary study results like in standard meta-analysis[91] was not possible. We aimed for a system that weights the underlying studies regarding their quality and therefore including their results weighted accordingly in our calculations. Within the scope of classic meta-analyses[92], the studies' individual quality is estimated according to their reported standard error (SE), which is understood as a measure of uncertainty: the smaller the SE, the higher the weight that is assigned to the regarding the source. Due to the varying estimation methods of considered studies, the majority of considered papers does not report measures of deviation for their results. These state definite values; therefore, there is no information about the precision of the results at hand. Against this background, we have decided to use a modified approach to estimate the considered papers' qualities[93]. Following van Ewijk et al.[94] and Haase et al.[95], we apply three relevant context-sensitive variables to approximate the standard error of the dependent variable and thereby evaluate the quality of each publication: the newer the paper (compared to the timeframe between 1995 and 2018), the higher we assume the quality of reported results. The more often a paper was cited per year (measured on the basis of Google Scholar), the higher the paper's reputation. The higher the publishing journal's impact factor (measured with the SciMago journal ranking), the higher its reputation and therefore, the paper's quality. For every paper, the three indicators publishing year (shortened with PY in Table 2), citations/year (CY), and journal rank (SJR) rank a paper's impact on a scale from 1 to 10, where 1 describes the lowest qualitative rank and 10 the highest. The sum of these three factors (SUM) then determines the weight of a paper's result in the mean value (WEIGHT). The papers' reported emission differences between organic and conventional (diff. org/conv) are weighted with the papers' specifically calculated WEIGHTS and finally aggregated to the emission difference between both systems.

With this approach, we weight results of qualitatively valuable papers higher and are therefore able to reduce the level of uncertainty in the estimated values because standard errors could—due to inconsistencies in the underlying studies—not be used. The results of this meta-analytical approach are listed in Table 2 (cf. "Results" subsection on quantification); further details can be found in Supplementary Note 1 and Supplementary Table 1. The studies considered compare GHG emissions of farming systems in relation to the crop/farm area. However, since our study aims to compare GHG emissions in relation to the weight of foodstuff, we include the difference in yield (yield gap) between the two farming systems for plant-based products and the difference in productivity (productivity gap) for animal-based and dairy products. For plant-based products, the yield gap is 117%, meaning that conventional farming produces 17% more plant-based products than organic farming in a given area. This gap was derived from three comprehensive meta studies[57–59] and weighted as just described for the emission difference between organic and conventional farming. For animal-based as well as dairy products, the productivity gap could be determined with the same studies used for the meta-analytical estimation of the emission differences[22–25,28,95]. The productivity gap is 179% for animal-based and 152% for dairy products. In line with Sanders and Hess[63], the yield (or productivity) difference $\frac{yield_{conv}}{yield_{org}}$ affects the calculation of the food-weight-specific emission difference $\frac{GHG_{org\ food\ weight}}{GHG_{conv\ food\ weight}} = D_{org/conv}$ between both farming systems: the yield difference is hereby multiplied with the cropland-specific emission difference $\frac{GHG_{org\ cropland}}{GHG_{conv\ crioland}}$. Resulting from this, the emission difference can be formulated as follows:

$$D_{org/conv} = \frac{GHG_{org\ food\ weight}}{GHG_{conv\ food\ weight}} = \frac{GHG_{org\ cropland}}{GHG_{conv\ cropland}} \times \frac{yield_{conv}}{yield_{org}} \qquad (1)$$

If the yield difference were not included, emissions from organic farming would appear lower than they actually are as organic farming has lower emissions per kg of foodstuff but also lower yields per area. With formula 1, we adjust for that.

Input data for monetization. Monetization of these externalities requires data on GHG costs as well as data on the food categories' producer prices.

The cost rate for CO_2 equivalents used in this study stems from the guidelines of the German Federal Environment Agency (UBA) on estimating external ecological costs[32]. They recommend a cost rate of 180 € per ton of CO_2 equivalents. This value is very close to the value of the 5th IPCC Assessment Report (173.5 €/tCO_2eq), where the mean of all (up to this point) available studies with a time preference rate of 1% was determined[33]. The cost rate from the German Federal Environment Agency's guideline is based on the cost damage model FUND[96] and includes an equity weighting as well as a time preference rate of 1% for future damages. In this model, different impact categories are considered in order to estimate external costs from GHG emissions. Damage costs can be differentiated as benefit losses such as lowered life expectancy or agricultural yield losses and costs of damage reduction such as medical treatment costs or water purification costs[97]. Following UBA, these damage costs are analyzed in the following categories: agriculture, forestry, sea-level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems[96]. Using a cost-benefit-analysis (CBA), an adequate level of emissions is reached when marginal abatement costs are equal with damage costs. In a CBA external damage, costs can therefore be conceptualized as a price surcharge necessary to effect their optimal reduction[98].

For the pricing of the food categories, we determine the total amount of proceeds that farmers accumulate for their sold foodstuff in €[99] for each category (producer price) divided by its total production quantity. Thereby we calculate the relative price per ton for each foodstuff. We solely refer to producer prices as the system boundaries only reach until the farmgate.

Calculating output data. Output data include the aggregation and separation of food-specific categories to the broader categories of animal- and plant-based products, as well as conventional and organic products. As previously explained, such aggregation and separation are needed because the underlying material-flow analysis tool only lists food-specific emission data for conventionally produced foodstuff. Combining the input data, we are now able to quantify and monetize externalities of GHGs for different food categories.

For quantification, we separate between the following two steps: first, the aggregation of emissions data to broader categories and second the differentiation between conventional and organic farming systems. We iterate these steps two times, once for broad categories of animal-based products, plant-based products,

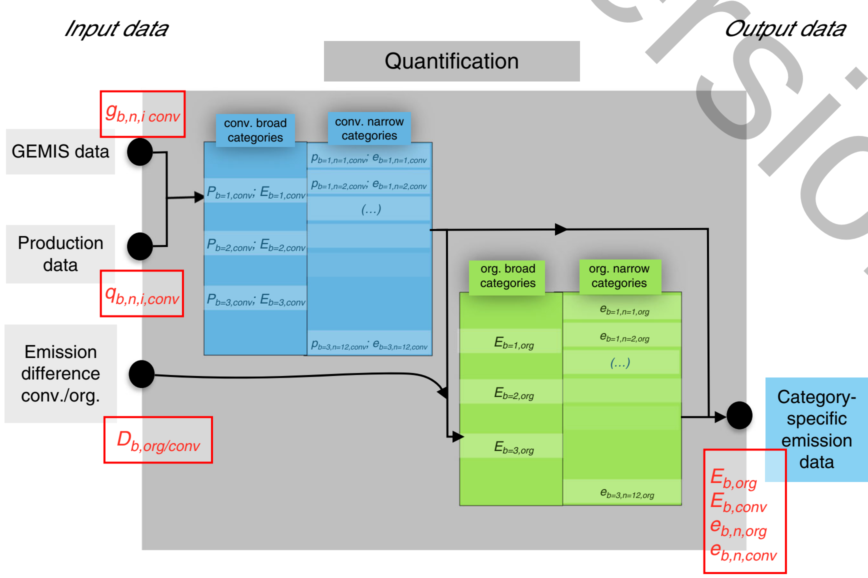

Fig. 4 Visualization of the quantification process. Quantification as well as corresponding input and output data are displayed. Data from the Global Emissions Model for Integrated Systems (GEMIS)[44] ($g_{b,n,i,conv}$) and production data[88–90] ($q_{b,n,i,conv}$) are combined, and emission data for broad ($E_{b,conv}$) and narrow ($e_{b,n,conv}$) categories are derived for conventional production. Organic emission values are calculated by multiplication of conventional emission values ($E_{b,org}$ and $_{eb,n,org}$) with the emission difference ($D_{b,org/conv}$) (cf. "Input data for quantification").

and dairy and once for more narrow categories of vegetables, fruits, root crops, legumes, cereal, and oilseeds on the plant-based side as well as milk, eggs, poultry, ruminant, and pig on the animal-based side. Figure 4 displays the whole process of quantification schematically before we describe it in detail in the following text.

Concerning the reasoning behind the method, the question that might come to mind is why the differentiation between farming systems happens after the aggregation and not before. This is due to the fact that the proportional production quantities of specific food as well as food categories to each other differ from conventional to organic production. Let us imagine aggregation would take place after the differentiation of farming systems: for example, beef actually makes up over 50% of all produced food in the organic animal-based product category, while it only accounts for 25% of the conventional animal-based product category (cf. production values in Table 3). As beef production produces the highest emissions of all foodstuffs, these high emissions would be weighted far stronger in the organic category than in the conventional category and thereby producing a higher mean for the organic animal-based product category than for the conventional one. As can be seen from this example, the organic animal-based product category could have a higher mean of emissions than the conventional animal-based product category while still having lower emissions for each individual organic animal-based product than conventional production. Deriving GHG emissions of foodstuff before aggregating to broader categories would thus be problematic and create means not representative for the elements that make up the broader category. To prevent this problem, the chosen method in this paper is thus to first aggregate to the chosen level of granularity (broad or narrow food categories) and then to derive emissions of organic production from conventional production data.

The first step of aggregation consists first of aggregating food-specific emission data from GEMIS $g_{b,n,i,conv}$ to the narrow categories $e_{b,n,conv}$ and second aggregating emission data from the narrow categories to the broad categories $E_{b,conv}$. As mentioned before and remarked in the respective indices, all these data only refer to conventional production up to this point. For both steps, the method is identical. The aggregation to narrow categories is represented in (2a) where $e_{b,n,conv}$ stands for the emissions of the narrow category n, which itself is part of the broad category b. Input data from GEMIS are remarked as $g_{b,n,i,conv}$, whereby the index i refers to the ith element of category n. It's production quantity is $q_{b,n,i,conv}$. $p_{b,n,conv}$ represents the production quantity of the narrow category n. I (and N in formula 2b) represents the highest index of an element in a narrow (or a broad) category.

$$e_{b,n=x,conv} = \sum_{i\in n=x}^{I} g_{b,n,i,conv} \times \frac{q_{b,n,i,conv}}{p_{b,n,conv}} \tag{2a}$$

The aggregation to broad categories is described by formula 2b whereby $E_{b,conv}$ are the emissions and $P_{b,conv}$ the production quantity of broad category b.

$$E_{b=x,conv} = \sum_{n\in b=x}^{N} e_{b,n,conv} \times \frac{p_{b,n,conv}}{P_{b,conv}}. \tag{2b}$$

In the second step, we calculate emission values for organic production by multiplying the calculated emission difference $D_{b,org/conv}$ between both farming systems (cf. "Input data for quantification") with the conventional emission values. These organic emission values are denoted as $E_{b,org}$ for broad categories and $e_{b,n,org}$ for narrow categories.

To calculate the costs C_b of category-specific emissions, we multiply the cost rate P for CO_2 equivalents with the category-specific emission data E_b or $e_{b,n}$ (depending on whether broad or narrow categories are observed). Further, we determine percentage surcharge costs Δ_b by setting these costs in relation to the producer price pp_b of the respective food category: $\Delta_b = \frac{C_b}{pp_b}$ (the calculation is analogue for narrow categories). These surcharge costs represent the price increase necessary to internalize all externalities from GHG emissions for a specific food category.

Dealing with uncertainties. Due to the interdisciplinarity and novelty of our study, we connect several methodological approaches and refer to various sources for data. Against this background, we had to accept some uncertainties while assembling and using the developed framework for our calculation. The studies included in our meta-analytical approach of calculating the difference between organic and conventional emission values, for one, are not fully consistent in the methodologies each of them uses (refer to Supplementary Table 1 for details). Furthermore, from the results of all included studies, it is apparent that there exists a wide range of emission differences between the farming practices, depending on the paper's scope and examined produce[21]. We attempted to account for this by performing the studies according to their fit regarding the object of research (cf. "Input data for quantification"). Due to insufficient availability of the data for the emission differences between organic and conventional on the basis of each narrow category, an average for the emission difference was used. This possibly results in imprecisions during the internalization of the external costs on the level of all narrow categories. Therefore, we focus on the aggregated broad categories, as this uncertainty can be evaded here. Furthermore, the in literature reported price factor for CO_2 equivalents is volatile over time, impacting the results of this paper. It is to be expected that the external costs of GHG emissions are likely to rise in the future (cf. subsection on research aim and literature review). Also, our study's scope is confined to the assessment of the current production situation within the German agricultural sector. Therefore, we do not account for future developments regarding a changing agricultural production landscape after internalization of the accounted external costs. We do, however, discuss possible effects on demand patterns as well as the environmental and social performance of the agricultural sector in "Discussion". Regarding the incorporated LUC emissions, there appears to be a lacking scientific consensus on a general method of calculation for such emissions[45,100–102]. We thus want to emphasize that these additional emissions should be treated with caution and are thereby displayed separately from the other data.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated and analyzed during the current study are available in the Center for Open Science repository, https://osf.io/e7v8x/?view_only=0bff6aa858a340df9046816c1404a51c. The datasets are derived from the following databases: German Federal Office of Statistics (https://www-genesis.destatis.de/genesis/online), German Society for Information on the Agricultural Market (AMI) (https://www.ami-informiert.de/), KTBL-Standard Gross Margins (https://daten.ktbl.de), EU Open Data Portal (https://data.europa.eu/euodp/en/data/dataset/uLrJZE2PQkMHod6feE8gXQ), Eurostat (https://ec.europa.eu/eurostat/databrowser), German Federal Office for Agriculture and Food (BLE) (https://www.ble.de), German Head Organization of Ecological Food Economics (BÖLW) (https://www.boelw.de/), Expert Agency for Renewable Resources (FNR) (https://fnr.de/), and the German Federal Ministry for Food and Agriculture (BMEL) (https://www.bmel-statistik.de/). More detailed information is provided in the source data file. Microsoft Excel (for Mac, version 16.16.26) was used to calculate and analyze the data of this study. Emission values were derived from the publicly available material-flow analysis tool GEMIS (Version 4.95), which can be downloaded here: http://iinas.org/gemis-download-121.html. Source data are provided with this paper.

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Author contributions
T.G. supervised the project. All authors developed the concept and designed the framework. M.P. and A.M. gathered the data. All authors discussed the results and implications. M.P. wrote the paper. All authors contributed equally and extensively to the revision process.

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Appendix C

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Please find the manuscript in the following pages.

Title: Land use change and dietary transitions – Addressing preventable climate and biodiversity damage

Authors: Moritz Hentschl, Amelie Michalke*, Maximilian Pieper, Tobias Gaugler, Susanne Stoll-Kleemann

Abstract: Land use changes (LUC) cause a large share of anthropogenic greenhouse gas emissions and endanger global biodiversity. Although LUC appear mainly as loss of tropical rainforest, the drivers can be located in regions of the global north, importing large quantities of agricultural goods from tropical countries. The aim of this study is to quantify and monetize the LUC impact caused by consumption of animal-based food in Germany as a case study and subsequently explore potentials for dietary transitions. We calculate the LUC impacts related to German animal-based food consumption with a combination of a land-balance, emission, and physical trade model. In particular, we determine CO_2 emissions caused by LUC as well as therefore deforested areas with associated biodiversity losses. Following the true cost accounting approach (TCA), the calculated LUC impacts are then monetized in order to approximate the related external costs of German food consumption. Our results show that German consumption of animal products causes 16.4 kha of deforestation annually (investigation period from 2013 ‑ 2016). Out of 6 analyzed product groups, the largest share of deforestation relates to milk (35%) and pork (33%), while, in terms of relative impact, beef has the highest climate impact from LUC with 0.75 tCO_2 per ton. Monetizing LUC externalities results in societal costs of 1.1 billion € (plus 0.5 billion € for biodiversity loss) annually caused by German food consumption of animal origin. Results also show that imported animal-based products emit only slightly more LUC related CO_2 emissions than those produced in Germany. There is a great urgency for political measures as well as shifts in consumer behavior if

sustainability goals are to be achieved. Both sides need to strive for a dietary transition towards more plant-based diets

Keywords: Dietary transition, Land use change (LUC), True cost accounting (TCA), Virtual land use, Sustainable agriculture

Supplementary Information is available in the electronic copy submitted with this dissertation.

1. Introduction

Considering the main drivers of climate change, household consumption causes a majority of the environmental burden (Ivanova et al. 2016). This sector creates 72% of global greenhouse gas (GHG) emissions, with the largest share of about 20% in total occurring through food consumption (Hertwich and Peters 2009). During the food production process, emissions arise at various points along the value chain. In addition to the demand for energy, water, and other inputs, land consumption is supposedly the most visible environmental impact of food production. Approximately 37% of the global land area is currently used for agricultural purposes (FAO 2020d). More than three quarters of this agricultural land is used to produce animal-based products with livestock farming and feed production included (FAO 2020d, Steinfeld et al. 2010). Products like beef or soy put enormous pressure on the resource of land and are consequently some of the most threatening commodities for natural ecosystems (von Witzke et al. 2011, Ponsioen and Blonk 2012). Further, the IPCC shows land use change (LUC) to be the main driver of agriculturally borne GHG emissions, with about 40% coming from LUC and forestry (Smith et al. 2014). Before this background, tackling LUC appears to have big potential for reducing further agricultural GHG emissions as well as containing current rates of biodiversity loss.

Although LUC for the creation of agricultural area primarily occurs in tropical countries, the drivers of deforestation can be located elsewhere (Henders et al. 2015, Fuchs et al. 2020, Karstensen et al. 2013). Dietary patterns in the global north characterized by high intakes of meat and dairy products are considerably more land-intensive than diets consisting of more plant-based products (e.g., vegan or vegetarian) (Aleksandrowicz et al. 2016). The area currently used for agriculture would have to be tripled or doubled, if the global population were to eat on average the same as people from the US or Germany, respectively (Alexander et al.

2016). Such land-intensive consumption patterns of animal-based food causes domestic land becoming too scarce to meet the demand for food.

Consequently, the deficit of domestic land must be compensated by virtually importing land, potentially leading to deforestation abroad. As virtual trade of land, and with it physical trade of agricultural goods, increases, the spatial distance between production and consumption of food items widens (Kastner et al. 2011). Consequently, complex, and non-transparent value chains increasingly blur the lines of responsibility for social and environmental damage and hinder identification of liable actors within the food sector (Clapp 2015). Described issues arising from international food production and trade need to be addressed with appropriate international measures for which transparency along the value chain is necessary (Dauvergne 2010; Clapp 2015).

Studies aiming at a quantification of external effects from LUC mostly refer to the production countries of deforestation-driving commodities without discussing the countries where these products are actually consumed. Ponsioen and Blonk (2012) for example, calculate carbon emissions of various agricultural products for Argentina, Brazil, Indonesia, and Malaysia. Kastner et al. (2014) furthermore analyze global trade flows of agricultural land and hence are able to include the influence of consumption patterns. However, individual products responsible for LUC emissions are not considered. A combination of global food-trade and the analysis of consumed agricultural products is presented by Henders et al. (2015) for some forest-risk commodities, or for clustered groups of the majority of agricultural commodities by Pendrill et al. (2019). The analyses show that Europe is one of the main importers of virtual land. However, they do not yet disclose LUC impacts and the connection to individual countries' consumption habits.

Opacity about the ecological damage of food products likewise challenges consumers and policy makers. Since actual environmental damage of foodstuff is not disclosed on products' labels, ecologically informed purchasing decisions are currently based on more obvious factors like the country of origin or the underlying production practice (e.g., organic foods) (Shi et al. 2018). However, these factors do not sufficiently reflect the environmental impact, and consumers significantly underestimate consequential environmental costs (Camilleri et al. 2019). Providing more information – for example in the form of an eco-label or increased prices – together with other measures could change consumers' purchasing decisions towards more sustainable products. Nevertheless, such labels could also lead to confusion as consumers understandably lack knowledge about the complexity of agricultural production and associated environmental impact (Feucht and Zander 2018). It also adds another variable to the already intricate decision process of food consumption for the consumer. Besides their own financial interest, they would now also have to contemplate social and ecological factors in the grocery store.

Another approach leading to more transparency while not adding to decision complexity substantially is the true cost accounting (TCA) method, which quantifies external effects, monetizes and finally internalizes them into the market price of a product (Gaugler and Michalke 2017; Pieper et al. 2020). Pricing environmental damage would give sustainable producers a competitive advantage and thus financially incentivize a reduction in environmentally damaging agricultural practices (Springmann et al. 2017). It would also encourage consumers to buy the more sustainable and consequently cheaper foods (Pieper et al. 2020).[1]

We do acknowledge that a mere monetary evaluation of natural damages would gloss over the incommensurability of natural values and the limited applicability of monetary units as a basis for nuanced political decision-making (Spash 2015). That being said, we decided on a twofold approach, in which we present not only monetized values of LUC impacts on biodiversity, but also the corresponding amount of CO_2 emissions in tons (t), and deforested area in hectare (ha). Aware of the difficulties and scientific controversy concerning the monetary valuation of environmental damage, we consciously decided in favor of TCA. Even if the underlying values of external cost factors cannot be guaranteed to represent the entirety of externalities, a valuation (regardless of its type) is more sensible to us than no valuation and its associated - implicit – rating with a value of zero.

[1] It should be noted that methods of monetization are criticized in ecological economics for disregarding the multiplicity and incommensurability of natural values and thus not allow for transparent decision-making (Spash and Aslaksen 2015). Thus, a decision-making process involving monetized damages to climate and biodiversity would need to respect the complexity of nature and integrate it in social, ecological, and economic processes.

Pretty et al. (2001) pioneered the scientific analysis of internalizing external effects of the agricultural sector. At present, studies continue to focus on the internalization of externalities, examining the effectiveness of TCA in connection with agricultural commodities (Negowetti 2016). This is usually only done qualitatively, without an actual quantification and following monetization of externalities. Consequently, Negowetti emphasizes the importance of further data collection about so-called true costs in order to allow more substantiated decisions at political level. Poore and Nemecek (2018) follow up on this notion ‑ at least quantitatively, not yet monetizing examined effects, however – with the most comprehensive agricultural life-cycle assessment (LCA) study to date. They show that monitoring multiple impacts especially during the farm-stage of food production and adjusting dietary behavior accordingly would drastically reduce the environmental impact of food consumption. It does not, however, explore possible financial incentives for consumers that would be created if TCA is applied. As Poore and Nemecek (2018) have shown, a consideration of only singular pollutants arising during the production process is insufficient.

To apply TCA and thus set incentives for consumers, it is necessary to quantify external effects as precisely as possible. Current work on LCA, however, is oftentimes limited to emissions during production. LUC is thus excluded, as it entails emissions that arise before production. Drivers of environmental damage like water management or eutrophication are already analyzed within LCA work, but LUC lacks attention in LCA as well as in TCA. This study aims to close this research gap by observing impacts of LUC in detail. Especially LUC impacts from animal-based production play a significant role in agriculture (Pieper et al. 2020) and should therefore not be neglected.

Recent studies suggest that TCA is especially reasonable when emissions can be distinguished between different products (Michalke et al. 2019, Pieper et al. 2020). While Poore and Nemecek (2018) show that a differentiation between food categories in the case of LUC is indeed necessary – LUC causes 24% of total GHG emissions of beef, 17% of pork and 37% of poultry production – current literature on the consequences of LUC is missing a reasonable connection between changed land in critical regions and the explicit consumption in importing countries differentiated for commonly consumed food commodities. Furthermore, a connection to economic implications of this background and potentials for dietary transitions are yet to be explored.

To build upon existing research and examine LUC related externalities of land-intensive foodstuffs and its interdependencies with dietary behavior change in greater detail, we conduct a comprehensive LUC analysis for animal-based food. Subsequently, this method is applied within a case study to German consumption by calculating corresponding external costs of six animal-based products (namely beef, pork, dairy, eggs, sheep/goat meat, and poultry) including LUC impacts of six feed crops (namely wheat, barley, maize, soy, rape/mustard seed, and rye). While we acknowledge the complexity and heterogeneity of agricultural systems, we decided to not make distinctions about the farming systems in which feed crops were cultivated for reasons of data availability and uncertainty minimization. Therefore, the products analyzed here describe average German animal-based food. The built framework is applied during the period from 2013 to 2016.

The following sections will first establish the method for quantifying LUC in different countries to meet German consumption with the use of land-balance, emission, and trade models. Models that were previously established in literature are adapted and extended for explicit use in the underlying case study. After land areas and emissions are quantified, arising costs related to CO_2 emissions and biodiversity losses are monetized. Subsequently, the potential for dietary transitions resulting from foodstuff specific TCA is introduced.

2. Methods and Data

2.1 Research Approach

An overview of the method to quantify land area used and GHG emissions caused from LUC, and the allocation of these to German food consumption is shown in Figure 1. The method consists of three models: the land-balance model (1), the emission model (2) and the physical trade model (3). The land-balance model (1) allows to allocate forest loss to the new types of land use, cropland, and pasture. The emission model (2) is used to calculate net carbon changes resulting from the loss of above ground biomass (AGB), below ground biomass (BGB) and soil organic carbon (SOC) due to LUC examined in the previous land-balance model. Results from (1) and (2) are linked with trade flows of the physical trade model (3), which allows tracing traded feed and animal products across international markets. Linking deforestation impacts calculated in (1) and (2) to the trade flows in (3) reveals ecological consequences of a country's consumption.

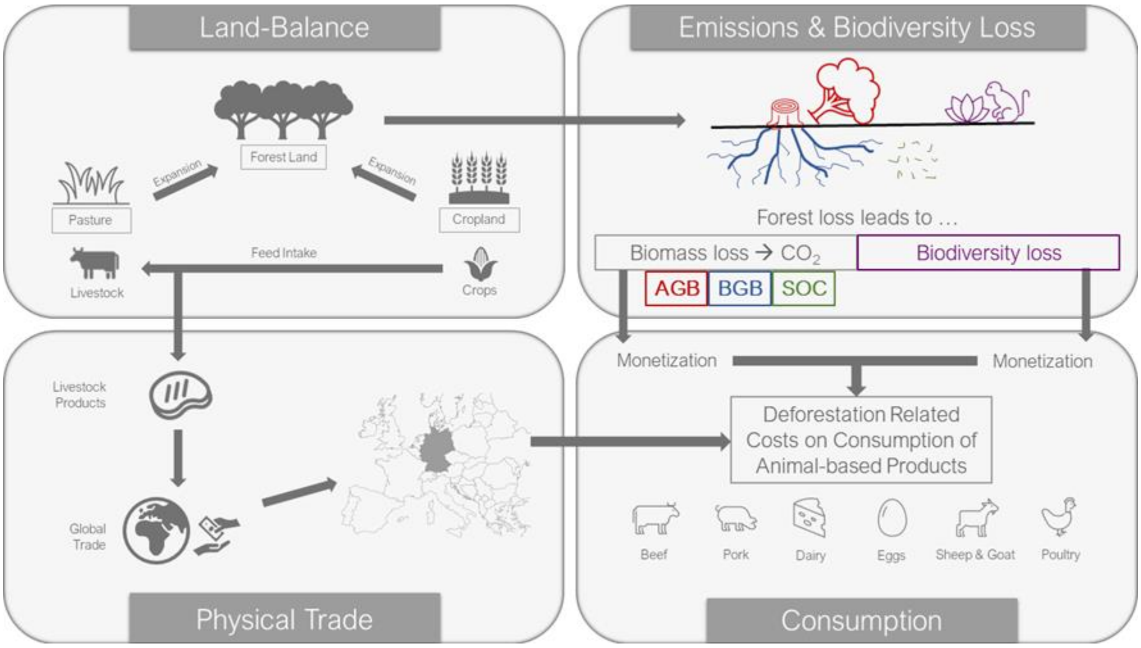

Figure 1: Overview of models used to calculate LUC impacts caused by the consumption of animal-based products[2].

In this study, we analyze the consumption of six animal-based product groups in Germany including their LUC impacts from feed production. The described method is based on Pendrill et al. (2019), and further expanded according to this study's specific aims. While the updated dataset of Pendrill et al. (2020) mainly shows the LUC impacts of plant-based commodities and beef, we analyze the impact of most animal-based products. More modifications to the approach are made to fit this research aim. They are explained in detail in the following sections and shortly summarized in the following. First, the product groups milk, and sheep/goat meat are included into the attribution of pasture. Second, while some countries analyzed by Pendrill et al. (2020) are not considered in the analysis of direct LUC impacts through the land balance model, other countries are additionally examined. The selection of countries was based on their geographical location in (sub)tropical areas where LUC plays an important role and on their relevance as trading partners of the case study's country, Germany. An overview of countries

[2] The map of Europe was created with mapchart.net. The icons for "Crops", "Pasture" and "Livestock Products" are made by Freepik from flaticon.com.

analyzed by LUC impacts can be found in Table S1, Supplementary Material. Third, the model steps are extended by the true cost accounting approach monetizing CO_2 emissions and biodiversity loss due to LUC. Fourth, in total six animal-based product groups are analyzed by their LUC impacts including the feed used for production. As we modified and partly extended the methodology, results differed from the base model but in accordance with the scientific scope of this study.

2.2. Land-balance model: Deforestation

Within the first model, forest loss globally is allocated to its new land use and is furthermore allocated among the various animal products and feed crops. The basis of the land-balance model is satellite remote sensing data from Hansen et al. (2013) on annual gross forest loss per country. The annual forest loss is allocated to cropland and pasture according to their expansion rates estimated with land use data from FAO (2020d) and Li et al. (2018) covering the period of 2002-2018. This is done whilst preventing potential overestimation of deforestation allocation (for details cf. Supplementary Material, section "Land balance model: deforestation"). An integrated condition of the land-balance model (also preventing overestimation) is the land use transition of cropland. If a gross loss of pasture exists, cropland first expands onto pasture and only then onto forest land as this is a common land use transition in Latin America (Graesser et al. 2015).

After attributing forest loss to the new land use of cropland, deforestation is further attributed to individual feed crops by determining area expansion with data on harvested areas from FAO (2020b) for the years 2003-2018. We selected the feed crops of wheat, barley, maize, soybean, rape and mustard seed and rye since they are most commonly used as feed in Germany (FAO 2020a). The forest loss allocated to pasture is further divided among different ruminant products (beef, goat and sheep meat, and dairy) similarly by estimating expansion with data on production quantities from FAO (2020e) and land use intensities from von Witzke et al. (2011). The six animal-based product groups are adapted from the listing of FAO (2020e). A product group includes both the primary product (e.g., in the case of "Milk, Total" this is "Milk, whole fresh cow") and its most important secondary or processed products (following the example of "Milk, Total", such processed products would be e.g., cheese or yogurt).

All annual area changes of cropland and pasture, and subsequently of individual feed crops and ruminant products are averaged over three years after the forest is lost. This accounts for the time lag between forest loss and establishment of production. Since data on land use from FAO (2020d) are available until 2018, the temporal boundaries of this model are years 2013 through 2016. In total, we examine 127 countries for deforestation impacts consisting of 106 (sub)tropical countries and 21 countries with relevant trading relations to Germany (cf. Table S1, Supplementary Material). For countries not located in (sub)tropical areas, we added a criterion to check whether data on forest area loss actually matches real deforestation by agricultural expansion (for details, cf. Supplementary Material, section "Land-balance model: Deforestation").

2.3 Emission model: Deforestation and peatland drainage

After forest loss is attributed to expanding land uses and individual commodities in the (1) land-balance model, CO_2 emissions resulting from this forest loss are calculated and attributed in the (2) emission model described in the following. Area changes and CO_2 emissions of peatland drainage are calculated differently than for deforestation, which is described later in this section.

Emissions resulting from deforestation are quantified by determining carbon stock changes in three classes of biomass. Above ground biomass (AGB, e.g., stems, branches and foliage), below ground biomass (BGB, live roots > 2mm diameter) and soil organic carbon (SOC, live and dead fine roots and other organic material). Loss of AGB is provided by GFW (2020) at country-level. GFW combines the forest loss dataset of Hansen et al. (2013) with data on biomass density from Zarin et al. (2016), thus loss of AGB can be identified. It has to be noted that this model does not differentiate between human-made forest loss or loss occurring naturally, through natural fire, for example. Additionally, GFW provides CO_2 emissions resulting from the AGB loss by applying the factor of 1.83 tons of CO_2 per ton of biomass. A factor of this scale is commonly used as (a) the assumption of biomass consisting to 50% of carbon is widely approved (IPCC report from Penman et al. 2003, Chapin et al. 2002, Fearnside 1997, Fahey et al. 2005) and (b) the molecular-to-atomic-weight ratio (converting C to CO_2) is defined with 44/12 and used by e.g., IPCC 2006, or EPA 2020. Multiplying the carbon content in biomass (50%) with the CO_2 molar mass ratio of 44/12 results in 1.83 tons of CO_2 emitting from 1 ton of biomass.

The BGB loss is usually calculated regarding the amount of AGB with a so-called root-to-shoot ratio. Root-to-shoot ratios vary by global ecological zones from 0.20 in temperate zones to 1.06 in tropical shrubland (Mokany et al. 2006; IPCC 2006). Distributions of these ecological zones are considered in this study on country-level with data from The Global Forest Resources Assessment 2000 (FAO 2000). Equally to AGB loss, the amount of BGB loss is multiplied with the above described factor of 1.83 to determine CO_2 emissions. The calculated CO_2 emissions from AGB and BGB loss are attributed to the six feed crops and the three ruminant products regarding their expansion rates determined in step (1) land-balance model.

In addition to AGB and BGB, losses in SOC are considered in this study using factors from Don et al. (2011), which describe SOC stock changes when forests are converted into different land uses. Beside losses of carbon, we consider carbon storage potential in AGB and BGB by using factors from IPCC (2006) and the EU (2010) (further details cf. Supplementary Material, section "Emission model: Deforestation").

CO_2 emissions are calculated for the period from 2013 to 2016. However, in this study an amortization time of ten years after the forest loss is considered. This amortization should reflect the lifetime of producing crops and livestock outputs flowing from the former forest land into the economic cycle. Thus, although LUC is considered a one-time event, LUC damage is uniformly distributed (amortized) over ten years of producing crops and livestock outputs in this study. Sensitivity analyses show that results hardly change with an adapted amortization period of one or five years (Pendrill et al. 2019). Therefore, we adopt this approach. To determine a LUC carbon impact per ton, the amortized emissions are divided by the total production volume in the respective country with production data from FAO (2020b).

The calculation of LUC emissions resulting from peatland drainage must be considered separately from deforestation emissions. In the National Inventory Submissions of the UNFCCC (2020) annual data on area changes of organic soils and net carbon change in organic soils are provided. We used this data for the LUC categories 'wetlands converted to cropland' and 'wetlands converted to grassland' (estimated as pasture) for Annex 1 countries ('developed' countries) relevant to Germany's import of feed crops or animal-based products. In this study we consider peatlands that were drained during the years 2013 - 2016 only, while all peatland drainages prior to 2013 are attributable to the sector land use (instead of LUC) according to the underlying temporal boundaries. The input data on area and carbon changes in organic soils are attributed to the six feed crops for 'wetlands converted to cropland' and to the three ruminant product groups for 'wetlands converted to grassland', as fodder is cultivated on cropland and ruminants graze on grassland. This is done according to their relative expansion rate based on the land-balance model for deforestation.

2.4. Physical trade model and feed allocation

We use the physical trade (PT) model by Kastner et al. (2014), which analyzes physical quantities with particular focus on the food sector. Applying the PT model, we use bilateral trade data from FAO (2020c) for 237 countries and production data (FAO 2020b, 2020e) to trace back physical quantities along the supply chain. The model eliminates trade flows of intermediary countries and outlines the country of origin where examined agricultural commodities were produced, up to the country of actual consumption. In this study, the PT model is calculated for the six feed crops most commonly used in Germany (wheat, barley, maize, soybeans, rape and mustard seed, and rye) and six product groups covering the vast majority of animal-based food (beef and buffalo meat, pig meat, milk and products, eggs, sheep and goat meat and poultry meat). To trace the trade flow of a processed product, it is necessary to convert it to its primary equivalent by using conversion factors. As in Kastner et al. (2014), conversion factors are considered in tons of dry matter, using data from Alexander et al. (2017), FAO et al. (2020g), INRA et al. (2020), Leung et al. (1972), McCance and Widdowson (2015), and USDA (2015).

After applying the PT model, feed crops are differentiated according to their use. Quantities of feed used to produce livestock outcomes are integrated into the trade flows of the regarding livestock product group. Thus, the environmental impact can be allocated to the consumption of livestock products instead of the feed itself. However, the attribution of feed is done only for the six feed crops, ignoring other feed composites like roughage or green fodder. Such composites are not directly attributed to LUC impacts, but more indirectly by attributing forest loss to pasture expansion. For determining the amount of feed crops used, FAO (2020a, 2020f) provides data on 'Feed' available per country and year. These feed quantities are distributed among the six animal-based products by introducing distribution coefficients from Kastner et al. (2014). These distribution coefficients are calculated by (a) weighting factors for feed intensities and (b) production data on livestock products from FAO (2020e). Multiplying feed use data (FAO 2020a, 2020f) with the distribution coefficients results in a 6x6 matrix attributing six feed crops among six livestock products (further details cf. Supplementary Material, section "Feed allocation model").

In the first two steps, LUC impacts in terms of area converted and CO_2 emissions released are determined in the (1) land-balance model and the (2) emission model, while in the third step – the (3) physical trade model – consumption and import values are identified for Germany, including livestock products as well as feed crops. Both the LUC impacts and the amounts of consumption and imports are connected by introducing carbon impacts per ton of product. These carbon impacts are product-, year- and country-specific and enable a link between emissions and total trading volume (multiplication of the carbon impacts per ton with the trading volume in ton). Thus, LUC impacts are now attributed directly to German consumption of animal-based foods. For a numerical example to better understand the ways of calculation, please see the Results section.

2.5 True cost accounting of LUC impacts

In a fourth step of the methodology, we account costs for two different types of damages caused by LUC, namely (1) societal monetary damage due to climate change and (2) biodiversity loss. The cost factor for CO_2 emissions is taken from the German Federal Environment Agency (UBA 2019), which sets the costs at 180 € per ton of emitted CO_2eq for the year of 2016. This external cost factor is determined within the model FUND (Anthoff 2007), as part of the project "New Energy Externalities Developments for Sustainability" (NEEDS). FUND uses historical data, observations, and scenarios in a timeframe between 1950 and 2300 to depict losses to the economy, like lowered life expectancy or agricultural yield losses due to a changing climate. This cost factor is close to the value described in the 5th IPCC Assessment report (173.5 € /tCO_2eq – concluding this through a meta-analysis of all suitable studies; IPCC 2014), and therefore appears reasonable to use for the purpose of this paper. We multiply this cost factor with the previously calculated emission values to show societal monetary damage arising from LUC of German animal-based food consumption.

The second cost factor describes LUC damages to biodiversity and is likewise a result of the NEEDS project (Ott et al. 2006). Monetary biodiversity values are calculated using restoration costs, i.e., the costs that must be incurred to restore a defined "start"-ecosystem to a "target"-ecosystem. In this paper, the start-ecosystems that have to be restored are cropland and pasture, because LUC turns a given ecosystem into crop-producing land and land for livestock grazing, respectively. The target-ecosystem is forest or rainforest, as we assess LUC from forests caused by German animal-based food consumption. We do not include restoration costs for peatland in this monetary assessment, as there is no data available for this biome within the NEEDS project. Results of this evaluation might therefore present rather conservative because damage from peatland drainage would increase the calculated external costs.

The restoration costs describe costs arising through defined measures, like soil loosening or afforestation. These measures restore the original state of the more biodiverse ecosystem and therefore depict the economic value of biodiversity lost through LUC. Verdone and Seidl (2017) find that the benefits of restoration can outweigh its costs when also accounting for the value of public goods and services. This provides an economic incentive to restore previously degraded or damaged land and is hence a cost-effective tool for protecting biodiversity. Since this study determines the status quo of LUC ‑ which includes previously damaged land ‑ rather than future trajectories, the restoration costing seems more sensible than abatement costing, for example. The biodiversity strategy of the European Commission (2011) implemented the restoration of ecosystems as one of the targets, which puts the necessity of investing in restoration on the international political agenda. CE Delft (2018) uses the same cost factor within an LCA based externality assessment in their Environmental Prices Handbook for the impact category of land use. After adjustment for inflation the costs per one square meter of tropical forest changed to cropland in 2016 lies at 3.15€ on European average. Of course, biodiversity loss induced from German livestock consumption – especially due to feed use for livestock raising – does not occur in Germany itself, but in the countries, feedstock is imported from. However, since the countries affected by German induced LUC generally have lower prices and income levels than Germany (or Europe generally), the cost factors would be lower for these countries due to the methodology underlying to calculate restoration costs. This would underestimate costs of biodiversity restoration and distort results in favor of products causing high LUC. The cost factor for biodiversity loss is multiplied with previously calculated areas of land changed for German animal-based food consumption.

2.6 Limitations and uncertainties in methods and data

When describing global interrelationships of agricultural production, trade, and consumption, it is inevitable to make some abstractions and thus allow some degree of uncertainty in the results. Although steadily using the most reliable data available, we have to outline some limitations of our study.

First, in the land-balance model, we assume aggregation of forest loss and the respective replacing land uses at country level. This results in losing partial granularity of the forest loss dataset provided at a resolution of 30x30 meters by Hansen et al. (2013). By aggregating forest loss as well as expanding land uses at country level, the assumption of homogeneity is underlying for land use transitions. This can lead to uncertainties, especially for large countries. As Australia and Brazil account for the highest LUC impact in this study, this uncertainty affects such countries and should be noted when discussing and interpreting their impacts. However, in order to use an abstract model at global scale, reasonably simplifying complex and regionally different land use transition patterns is necessary. Therefore, we aggregate at country level (1) to analyze global land trade flows more practically and (2) to keep consistent with other data inputs available at country level (for the land-balance, and emission and trade models). To conclude, analyzing land use transitions at a more fine-grained resolution could be reasonable to identify local hotspots of LUC, but aggregating data at a more coarse-grained scale is an appropriate abstraction when observing global conjunctions.

Second, another assumption that needs indication of uncertainty is the land use transition of cropland expanding first to pasture (if a gross loss exists) and subsequently to forest land. This assumption is based on Graesser et al. (2015) who analyze processes of land use transition in Latin America. By adopting this land use transition, we aim to reflect reality in countries where LUC is a major threat to natural environments and exports of agricultural commodities to Germany are significantly high. As such countries are predominantly Latin American and cause the majority of LUC related CO_2 emissions driven by German consumption of animal-based food, we assume this land use transition to reflect reality well. Otherwise without using this limitation, forest loss would be drastically overestimated. However, for countries where land use transition processes differ from the assumed process, this assumption leads to uncertainties in their LUC impact. Still, it does not affect the overall extent of LUC impacts caused by German consumption of animal-based foods significantly.

Third, we want to touch on the large heterogeneity of studies monetarily evaluating environmental damage, as induced by GHG emissions, for example, but especially when it comes to biodiversity. Most widely recognized is the approach of valuing ecosystem services individually, leading to a total economic value of the ecosystem, which shows high variation within existing literature. With the herein used approach of restoration costs, however, we are using average European cost factors, which could potentially underestimate the damage done from LUC of forests in primarily the global south. We also did not include costs for changing peatland, another potentially underestimating factor. This evaluation of biodiversity costs therefore poses a rather conservative approach. Nevertheless, de Groot et al. (2012) conduct a meta-analysis and assess over 320 publications to monetarily value ecosystem services of different biomes. They find a value of 2.44 to 2.49€ per square meter of tropical forest, comparable to the herein used of 3.15€, especially considering the time frame of this study.

Fourth, in this study, CO_2 emissions from peatland drainage are of minor importance for the total LUC related environmental impacts according to our results. But peatland drainage actually is a key issue within climate change (Humpenöder et al. 2020). In Germany drained peatlands under agricultural land use emit 37,5 million tons of CO_2eq annually (UBA 2020). In contrast to this, we consider only the LUC related emissions with a significantly lower amount of CO_2 emissions than LUC plus land use. As emissions through peatland drainage itself are highly contested among researchers, the question of which agricultural products can be attributed for these emissions can only be answered comprehensively with further investigations. This also applies to other land uses such as uncultivated grasslands or savannas, which majorly contribute to carbon storage and biodiversity conservation globally as well.

3. Results

The following numerical example illustrates how LUC related emissions of a specific product are composed. Germany consumed 1,173,093 tons of beef and buffalo meat in 2016, of which 78% resulted from domestic production and 22% from imports. The feed used for domestic production of beef and buffalo meat originated to 65% from domestic production and to 35% from imports. The LUC related emissions of the feed imported for German production and used for beef and buffalo meat account for 480,313 tons of CO_2 (33% of which from soybean production in Brazil only). Additionally, emissions arising from the import of beef and buffalo meat account for 309,471 tons CO_2. In addition, the growing of feed used for animal-based food, which are then exported to Germany, also generated LUC related CO_2 emissions, amounting to 135,378 t CO_2. After calculating the "imported" emissions, peatland drainage emissions generated in Germany are added, which amount to 240 t CO_2. In total, German consumption of beef and buffalo meat in 2016 caused 925,402 tons of LUC related CO_2 emissions.

Such results are calculated for each of the six animal-based products and for each year between 2013 and 2016 respectively. Because no trends or significant fluctuations were observed we present the results as average values for these four years. Table 1 shows the quantities of products consumed in Germany, the resulting LUC impacts in terms of CO_2 emissions and deforested area as well as the monetized values of these impacts.

Milk products are consumed in the highest quantities of all animal-based products by far in Germany with over 25 Mio. tons. Concerning meat products, pork is consumed nearly three times as much as poultry and more than four times as much as beef. Contrary to this, sheep and goat meat is consumed in very small quantities and therefore has a rather small impact on total LUC related CO_2 emissions of German consumption. Eggs are consumed in similarly large quantities as beef, but their CO_2 impact is comparably small. Hence the consumption of eggs is also not as significant for total German emissions.

At 0.75 tons of CO_2 per ton of consumption, beef has the highest relative LUC related impact among all animal products. However, looking at the total LUC related CO_2 emissions, even though milk and pork have rather smaller carbon impacts (especially milk with 0.09 t CO_2 per consumed ton), they are the product groups contributing the highest share to total emissions. This is due to their high consumption volumes. Nevertheless, beef and poultry also increase total LUC related CO_2 emissions, although not to the same extent as milk and pork. In total, 5.98 million tons of CO_2 emissions from LUC alone result annually from the consumption of animal-based foods in Germany. This equals 9.12% of GHG emissions from the agricultural sector in Germany in 2016 and 0.66% of total GHG emissions in Germany (UBA 2021).

Table 1: Annual German consumption of animal-based products on average from 2013-2016, following quantified LUC related impacts in terms of CO_2 emissions and deforested area, and subsequent monetization of these impacts. In Table S2, Supplementary Material, related impacts in terms of CO_2 emissions and deforested area, and subsequent monetization of these impacts. In Table S2, Supplementary Material, relative LUC related CO_2 emissions are presented in tons of protein.

Animal-based product groups	Consumption	**LUC related CO_2 emissions**		**Deforested area**		**Monetized LUC impacts**	
	Consumption	Absolute	Relative	Absolute	Relative	CO_2 emissions (+ deforested area)	
	t	*t CO_2*	*t CO_2 / t*	*ha*	*m^2 / t*	*Million €*	
Beef	1,119,431	837,967	0.75	2,504	22.4	149.5	(+78.2)
Pork	4,679,423	1,961,219	0.42	5,439	11.6	349.8	(+169.8)
Milk and Dairy	25,006,598	2,170,904	0.09	5,759	2.3	387.2	(+179.7)
Eggs	1,110,431	208,816	0.19	578	5.2	37.2	(+18.1)
Sheep and Goat Meat	59,628	41,972	0.70	116	19.4	7.5	(+3.6)
Poultry Meat	1,718,533	765,636	0.45	2,019	11.7	136.5	(+63.0)
Total	33,694,044	5,986,514		16,414		1,067.8	(+512.4)

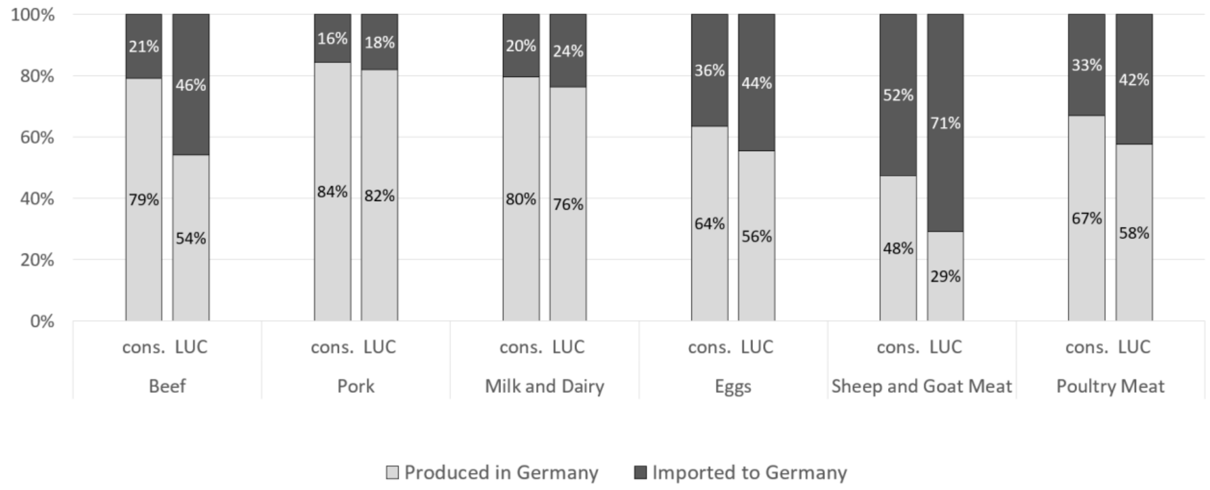

Figure 2: Shares of consumption quantities (‘cons.’) and LUC related CO_2 emissions (‘LUC’) caused by different animal-based food ‘produced in Germany’ and ‘imported to Germany’.

When considering deforested area, the distribution of LUC impacts between the products is very similar as described above. That is because most LUC related CO_2 emissions occur from deforestation (and not peatland drainage) according to the results of our method. Thus, milk and pork account for the largest part of total deforested area due to German consumption patterns. Beef and poultry consumption contribute significantly to total German deforestation as well, while eggs, sheep and goat meat consumption have less impact. Likewise, the distribution of area impacts between the livestock products is similar to the carbon impacts with beef consumption influencing deforestation the most, at 22.4 m^2 deforested area per ton of consumption. In order to meet German total demand of livestock products, a forest area of 16,414 ha is cleared annually. This slightly extends the size of Europe’s fourth smallest country Liechtenstein with 16,048 hectares. When analyzing the results, it should once again be emphasized that all LUC impacts relate only to the consumption of animal-based products and that Germany represents just 1.1% of the world’s population.

Next, evaluating LUC related CO_2 emissions and deforested area in terms of their respective damage costs of 180 € per ton of CO_2 and 3.15 € per square meter[5], results in economic LUC damage from German consumption of animal-based products. The annual monetary LUC impact amounts to 1.1 billion € for CO_2 emissions and 0.5 billion € for deforested area and its associated biodiversity losses, respectively. Thus, including externalities of biodiversity loss, LUC related costs amount to a total of 1.6 billion € per year. This would equal 13.4% of external costs if all GHG emissions caused by the German agricultural sector were monetized with 180 €/t CO_2eq. The same distribution pattern as for LUC related CO_2 emissions and deforested area among the different products appears with milk and pork. These products cause the highest monetary LUC damage, followed by beef and poultry, and lastly eggs, sheep and goat meat.

Figure 2 illustrates how much of the annually consumed amount of products originates from German production and how much is imported. For both cases, the associated CO_2 emissions are presented, whereas the values for German production are almost exclusively attributed to feed imports (as no deforestation is assumed in Germany itself as described in the section "Land-balance model: Deforestation") and to a small extent to peatland drainage for agricultural expansion in Germany. Similarly, for countries that are excluded from deforestation analysis (mainly in Western Europe), but are exporting animal products to Germany, the largest share of LUC impacts is caused by feed imports from countries with deforestation (e.g., Brazil). Overall, 79% of animal-based food consumed in Germany are produced domestically, while 72% of LUC related CO_2 emissions originate from German production.

This suggests that products from Germany cause only slightly less LUC impacts than imported goods, also displayed in Figure 3. For most products (and especially for pork and milk influencing the overall result strongly), the relative LUC related CO_2 emissions for imported foods are at a similar level to those for German production. However, for the other products, the carbon impacts between German and non-domestic production differ more. Especially for beef, the relative carbon emissions of imported beef exceed more than three times that of beef

[5] The cost factors presented relate to the calculation for 2016. These factors were discounted for calculating the years 2013 - 2015. Table 1 shows the average values of LUC impacts monetized for the years 2013 - 2016.

produced in Germany. Thus, contrary to other products, replacing imported beef with domestically produced beef would be one way to reduce LUC impacts.

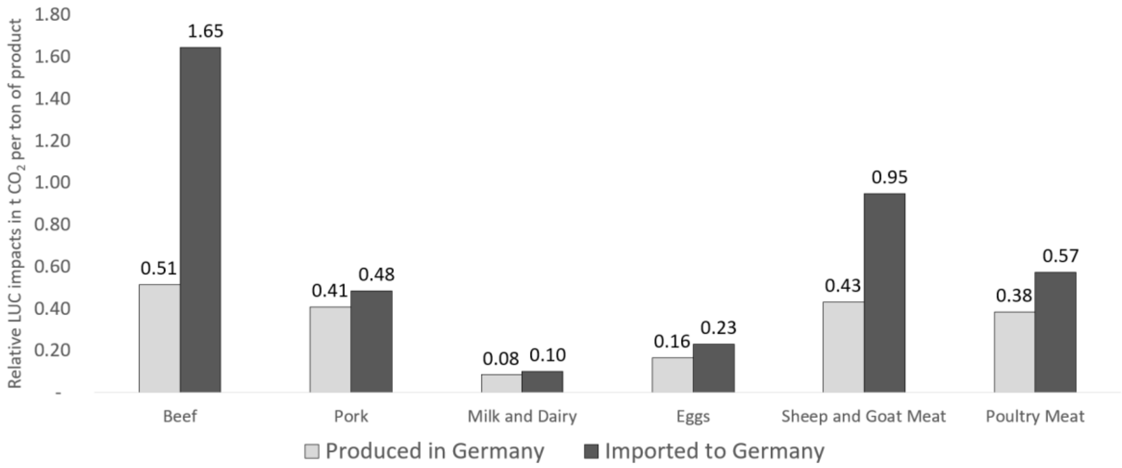

Figure 3: LUC related carbon emissions per ton of animal-based food ‘produced in Germany’ and ‘imported to Germany’.

The feed crops used for production of animal-based foods were also analyzed. In Figure 4, a Sankey diagram shows LUC related CO_2 emission flows of feed crops linked to their originating regions and to the animal-based products they were used for.

Figure 4 shows that for the year of 2016 soybeans, and rape and mustard seeds dominate the LUC impacts of feed crops. While LUC emissions from soybean expansion for German feed use arise primarily in Brazil, rape and mustard seeds caused high LUC impacts in Australia (with 2016 being a year of generally very high total LUC related emissions for Australia compared to the average of the years 2013 to 2016). Europe contributes mainly with rape and mustard seeds to Germany’s direct LUC related emissions, whereas LUC emissions in North, Middle and South America for German consumption are driven almost entirely from soybean expansion. Asia and Africa do not contribute significantly to LUC emissions of feed for German consumption of animal-based foods. The distribution of feed related LUC emissions is similar among all livestock products consumed in Germany with mainly rape and mustard seed, and soybeans being responsible for LUC related emissions of animal-based foods.

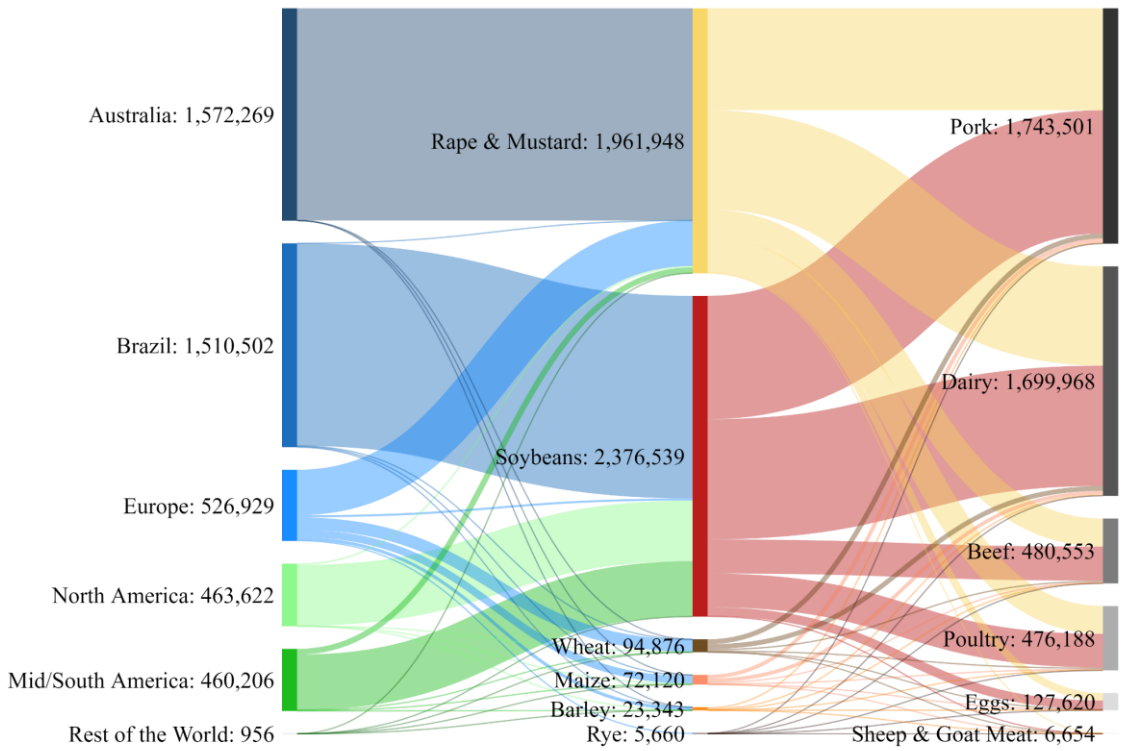

Figure 4: Shown are flows of LUC related CO_2 emissions of six feed crops used for production of animal-based foods consumed in Germany for the year of 2016. Regions where feed crop expansion caused LUC for German consumption are shown on the left-hand side. Only direct trade flows to Germany are shown, without indirect trade flows. Indirect trade flows refer to feed used abroad for the production of animal products that are subsequently exported to Germany. Since the LUC impacts of indirect trade flows are attributed to 'intermediary countries' and not to the countries of LUC origin, it would distort the correct distribution. For this figure, data on LUC related emissions of pasture expansion is not included.

4. Discussion

4.1 Comparison to preliminary work

The assessment of LUC areal value in Pieper et al. (2020), one of the only studies comparable to this monetization of LUC related external costs, underlies a different method compared to our study, leading to partly differing results. A comparison of price mark-ups shows that their results exceed ours by a factor of six for pork, and by a factor of ten for beef. However, such differences do not translate to the secondary animal-based products of dairy and eggs likewise as both, our study and Pieper et al. (2020), show a price mark-up of less than €0.05 per kilogram for both products. The large differences for the primary animal-based products of beef and pork can be mainly explained by different methods to calculate LUC emissions and to distribute feed impacts among animal products as well as underlying data to compute with. In a comparison with results of Sandström et al. (2018) similar differences are detectable. The authors calculate a value of around 30 Mt of LUC related CO_2eq for German food consumption annually. While 70% of this value equals the share of feed embedded in animal products (on EU average), their LUC impact is more than three times as high as the 6 Mt CO_2 from our study. Their used method for the calculation of crop expansion is more similar to that used in Pieper et al. (2020) than ours, so the differences in results can be explained again by methodological varieties.

Cederberg et al. (2019) present values close to our results for LUC related emissions across all animal-based products. The difference of their presented 0.073 t CO_2eq emissions annually per capita for food consumption in Sweden and our result of 0.074 t CO_2 is marginal. This is sensible, as both studies use the method of Pendrill et al. (2019) and corresponding data sources as the basis of their calculations.

Both the large differences (Pieper et al. 2020, Sandström et al. 2018), and very close similarities (Cederberg et al. 2019) of results within food-related LUC research shows that there is not yet a consistent methodology to attribute LUC emissions to food consumption and that research within this topic needs to be extended. It also confirms that the choice of methodology and data can cause significant changes in calculated results (Meul et al. 2012, Opio et al. 2013), reiterating the uncertainty of our study's and the previously discussed studies' results.

4.2 Implications and potential for mitigation

The underlying issue of profuse diets typical within the global north, which require a lot of land for livestock and feed cultivation, inevitably leads to a virtual import of agricultural land. As a result, LUC takes place in countries from which Germany – or the global north in general – obtains their animal feed products, as more agricultural land is required than is available to satisfy their currently prevailing consumption patterns.

Our results show that all animal-based products increase LUC, but for partly different reasons. For example, 1 ton of beef has the highest LUC impact compared to 1 ton of any other product and therefore, based on product tons, beef is the most damaging product regarding LUC. However, the consumption of pork and dairy products is also a major threat to forest loss, as these products are consumed in comparably large quantities and thus their LUC impact is high in absolute figures.

From Figure 4 implications could be drawn that a shift in the feed composition of livestock potentially leads to LUC reduction. Feed crops like rape and mustard seed, and soybeans cause disproportionately high LUC impacts compared to other feed crops used to the same extent (cf. Figure S4, Supplementary Material). However, replacing LUC driving feed in diets of livestock is hard to achieve as the high protein content and energy density of soybeans are important for feeding. The annual German demand of crude protein is 3.9 million tons, of which 1.5 million tons are produced domestically (Stockinger and Schätzl 2012). Of the remaining 2.4 million tons of crude protein, 95% are covered by soybean imports from Brazil, Argentina and the US (Stockinger and Schätzl 2012). Agricultural systems in Europe would need radical transformation to self-sufficiently satisfy this demand in crude protein for animal feed (de Visser et al. 2014). This would either mean a substantial increase of protein plant production or decrease of animal-based consumption in order to reduce dependency on imports of protein-rich plants for feed.

An auspicious option to reduce LUC impacts is the shift from animal-based food consumption towards a more plant-based diet (Alexander et al. 2016). Here, trends of slight decrease in the consumption of animal-based food can be observed in Germany since 2000 (BMEL 2021a, BMEL 2021b). However, looking more closely, while consumption of product groups with the highest volume, namely pork and dairy, decreased by about 16% and 6% over the last 10 years, respectively, consumption of other products, such as beef or poultry, increased by about 10% or 15% since 2010 (BMEL 2021a, BMEL 2021b). For beef, another trend becomes obvious. While gross domestic production of beef in Germany has decreased by 18% since 2000, the volume of imports increased by 68% (BMEL 2021a). If this persists, Germany will depend on imports of beef (in addition to the dependency of soy), which is crucial since imported beef causes more than three times as much LUC related CO_2 emissions as domestically produced beef (cf. Figure 3). A free trade agreement between the EU and export countries of LUC-risk commodities would encourage such trends and enhance pressure on natural lands. Therefore, action is needed to mitigate German dependencies on imports and additionally, to motivate decreasing animal-based food consumption since it is still on a high level in Germany (FAO 2020f). For example, Germany still ranks 13th in the world in terms of per capita consumption of pork (FAO 2020f), despite the decline in consumption over the last ten years. This study contributes to the discussion and motivation of reducing animal-product consumption as it provides better information on a crucial climate factor by attributing LUC to animal-based foods consumed in Germany.

There is currently no international agreement to account for consumption- or import-associated emissions, which is why an evaluation on national level – as done through this case study – might not bring about sufficient incentive to reduce emissions internationally. However, Germany has great economic and innovative strength in Europe as well as in the global context and is an important trading partner for many countries. If German businesses would implement TCA principles, this likely affects other countries. Further, if the EU's implementation of a carbon border adjustment mechanism is successful, there would be direct financial incentive for other countries to act accordingly. Second, if financial incentives showed German producers the need of reducing international LUC, an issue on international ground would be tackled. Land for German production would not be required in as great quantities as today and ecological benefits would be felt globally. Nevertheless, it is of course vital to investigate LUC impacts internationally to fully grasp the issues related to it.

Quantifying and subsequently monetizing LUC impacts of animal-based products as well as the huge environmental damage determined within this context imply the urgency of targeted measures. It is an urgent duty for governments to develop strategies that reduce damage to climate and biodiversity from virtual land use changes, with the help of regulatory and statutory measures as well as negotiations of trade agreements (Seymour and Harris 2019, WWF 2021, IDH 2020).

4.3 Consumers' behavior changes and dietary transitions

The presented results show that a dietary transition is necessary not only for the well-known reasons of animal welfare, health maintenance or reducing the climate crisis (Tilman and Clark 2014, Carlsson-Kanyama et al. 2009), but also to fight the negative impacts from LUC described above.

The practical consequences of our results and previous environmental studies on food consumption and production are a necessary and sufficient reduction in the consumed quantities of animal-based products (Steinfeld et al. 2010, von Witzke et al. 2011, Ponsioen and Blonk 2012, Aleksandrowicz et al. 2016). One novel way to achieve this is to implement true prices based on the presented calculations and especially with including more drivers of environmental impacts additionally to only LUC (Pieper et al. 2020). More conventional approaches, such as increasing knowledge on the negative consequences of animal-based diets, are not sufficiently successful on the behavioral level (Stoll-Kleemann and Schmidt 2017, Dibb and Fitzpatrick 2014, Kollmuss and Agyeman 2002). Very often, meat-eaters and also dairy consumers ‑ even if so to a lesser degree ‑ tend to avoid or resist information about the negative consequences of their food consumption behavior in order to overcome strong, emotionally distressing reactions. Therefore, including TCA into the pricing of foods seems an innovative and auspicious approach. Consumers would not have to take into account a multitude of ethical or environmental decisions but could rather optimize for their own personal economic interest solely. With a pricing design according to TCA this would likewise equally optimize sustainability of consumed goods and bring forward sustainable dietary transition (Springmann et al. 2017). This, of course, would have more effect if a magnitude of environmental impact were to be internalized into the market prices compared to the single driver LUC assessed in this paper.

An additional novelty brought forth with this analysis is further focus on the reduction of dairy consumption because the described negative consequences hold potential of reducing LUC impacts when intake is reduced. Because dairy consumption is less emotionalized than meat consumption, which is associated e.g., with masculinity (Sumpter 2015), this notion is probably easier to "sell" to end consumers. Current statistics of the German Federal Agency for Agriculture and Food (BMEL 2021b) confirm this assumption by showing that dairy consumption has been decreasing substantially. In general, interest in plant-based sources of protein is increasing. A number of replacement or alternative products have grown in popularity in recent years and provide opportunities to help consumers transition to a more plant-based diet (Schösler et al. 2012).

For successfully transforming to sustainable dietary behavior on a grand scale, it is important that opportunities and strategies are tailored in a target group-specific manner also related to the issue of dairy consumption. Also, approaches like consumer segmentation should be considered: when prices were to increase according to TCA, certain products would likely be hardly purchasable for financially disadvantaged consumer segments, especially with an assessment of more environmental drivers than only LUC.

5. Conclusion

The typical diet in countries of the global north is directly linked to LUCs abroad as domestic land is usually too scarce to satisfy domestic consumption. In this context, LUCs occur especially in the form of deforestation in South America or Australia as they are driven by area expansion for production of feed crops. To better understand this context, we present in this study an analysis that quantifies and monetizes the damage of LUC caused by German animal food consumption in terms of CO_2 emissions and biodiversity losses.

Results show that all animal foods consumed in Germany drive deforestation. However, the driving causes differ within animal food categories. Carbon emissions per ton of foodstuff is highest for beef, while pork and dairy cause the highest CO_2 emissions and biodiversity losses in total for Germany. Furthermore, results underline that the LUC impact of animal-based foods produced in Germany is only slightly smaller compared to imported animal-based products in most cases. Therefore, it is most efficient to strive for a change in consumers' dietary behavior towards more plant-based diets. To realize such dietary transitions, measures are required, both at policy and consumer level. Policy makers must find solutions to regulate, sanction or ban LUC and other threats to the environment, while consumers have to be aware of the consequences of their dietary habits. Only if both levels are successfully addressed in countries of the global north, like Germany, will we be able to reduce the LUC related CO_2 emissions and biodiversity losses caused by the global society's food consumption.

In this interdisciplinary study, we combine the research fields of environmental and resource economics with geographical datasets. This interdisciplinary approach offers many links for future studies in the social sciences (e.g., consumer behavior changes). With our findings – in this paper addressed in a case study focusing on Germany – we hope to contribute to a better understanding of the global picture of LUC impacts from animal-based food consumption when this framework will be used for other countries likewise. Furthermore, it is also reasonable to use our results to combine LUC with other (environmental) impact factors such as eutrophication or animal welfare. Embedding a precise determination of LUC impacts into LCA studies can result in a better overview of environmental damage drivers along the entire value chain of a product.

The monetization of LUC related climate impacts and biodiversity losses may help both to highlight the extent of environmental damage and to compare these different negative environmental impacts with each other. Nevertheless, the shortcomings of TCA are not to be neglected when drawing conclusions regarding a possible following dietary transition. First, potential future variations of climatic conditions, or changes in consumption values are hardly displayable in models such as the one presented here. Further, these variations, and other limitations, like those of underlying costing methods for example, burden a reasonable implementation. One cannot assume the calculated costs to be “true” indeed, since the complexity of agricultural production and its impacts is too high for a fully realistic representation through data. Also, since there are agricultural practices that can help increase biodiversity, a general implementation of averaged external costs would be unfair to environmentally and socially conscious producers and consumers.

With this work, we are able to express implications from LUC in the German context. But this is only one step towards reducing the overall LUC impact of food consumption. For a holistic shift in consumption patterns, in favor of the environment, and global societies likewise, there needs to be better understanding of beneficial production practices among beneficial foodstuff categories. Also, of course, Germany is one case study in which this model can be used. Comprehensive analyses on globally caused LUC abroad must be put forward.

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Appendix D

This paper is submitted for peer-review in the *Journal of Cleaner Production* in September 2022.

Please find the manuscript in the following pages.

Title: True Cost Accounting of organic and conventional food production

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Abstract: Agricultural activities are one of the biggest polluters globally. Consumers are misled towards demand of unsustainable and inadequately priced foodstuff by an insufficient internalization of externalities. A shift in demand towards more sustainable dietary choices can lead the sustainable transition of agri-food networks. We introduce a framework that evaluates environmental damage economically: we connect environmental assessment of different foodstuff with the internalization of its monetary impact. Life Cycle Assessments of conventional and organic foods are linked with True Cost Accounting to adjust food prices regarding their environmental impacts. Using this framework for 22 German agricultural products, we find that on average, plant-based production causes externalities of about €0.79 per kg for conventional, and about €0.42 for organic products. Conventional dairy and eggs induce additional costs of about €1.29 per kg on average, while in organic systems, they cause about €1.10 more. Conventional meat causes externalities of €4.42 and organic meat about € 4.22 per kg, with beef generating the highest costs of all. Environmental favourability of organic products is confirmed but resulting organic market prices after internalization still exceed conventional prices. Externalities represent a negative impact on societal welfare, which should be addressed with policies supporting transparent pricing approaches.

Keywords: Dietary transition, Land use change (LUC), True cost accounting (TCA), Virtual land use, Sustainable agriculture

Supplementary Information is available in the electronic copy submitted with this dissertation.

1. Introduction

The consumption and production of foodstuff is linked to a plethora of global crises. Agriculture is a major driver in global warming causing about a quarter of global greenhouse gas emissions (IPCC, 2014a). It is also the largest consumer of freshwater requiring 69% of withdrawals globally (UN, 2018), and is acknowledged as the primary 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 as the primary cause. These developments are continuously putting pressure on environmental and societal systems.

Achieving a transformation of current agricultural systems towards more sustainable production would help tackling these issues. Sustainability is described as a tripartite venture and should consider the environment as well as society and the economy (Purvis et al., 2019). However, current market prices do not reflect social and environmental damage caused by the production of foodstuff. The sector externalizes this damage, e.g., to other countries with land use for fodder production or to society with emissions threatening the global population and future generations. This externalization of costs does not follow the UN's polluter-pays principle (United Nations, 1992) and leads to market distortions: a considerably lower market price – without accounting for all consequences of production – results in higher demand, as seen in environmentally damaging dietary behavior, especially in developed countries (Behrens et al., 2017; Semba et al., 2020). Stiglitz (2000) defines externalities as one fundamental type of market failure. In order to maximize total societal welfare, the consume of foodstuff with high externalities must be reduced because high demand drives high production. This consequently increases agricultural environmental impact and perpetuates the cycle of ecological and societal damage. The internalization, however, of external costs would lead to reduction of unsustainable demand (Hussen 2004).

True Cost Accounting (TCA), aiming at internalizing external costs into the market price of products, has lately gained interest as an approach for policy measures improving the sustainability of the agricultural sector. TCA reports positive or negative impacts of a produced commodity in monetary terms that are not considered within production costs (Baker et al. 2020). Therefore, TCA is the combination of environmental (or social) assessment and a following cost (or benefit) analysis. The environmental assessment can be performed through Life Cycle Assessment (LCA), a common method for the evaluation of a variety of environmental impacts. While agricultural LCA studies often precisely evaluate specific impact categories, like GHG emissions (Aguilera et al., 2015; Flysjö et al., 2012; Venkat, 2012), or confine to single products (Bos et al., 2014; Buratti et al., 2017; Einarsson et al., 2018), a monetary 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 to calculate climate costs based on LCA for basic foodstuff. We follow on from this framework and aim to address the research gap in using a full LCA of various foods and farming practices combined with a monetary evaluation to eventually develop and establish a comprehensive TCA for food.

For this, we combine a comprehensive impact assessment of a variety of foodstuff with best-practice monetarization. We assess the life cycle impacts of 22 food products on 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 (EPH) (de Bruyn et al., 2018) and the Federal Environmental Agency of Germany (Umweltbundesamt, 2020) to depict the value of food with internalized externalities. This method eventually 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 associated external costs of these foods? How do producer prices change after the internalization of external costs according to the polluter-pays principle?

The remainder of this study first explains the underlying research design with used material, methods, and related calculations (section 2). Section 3.1 then presents the results in terms of environmental impacts of foodstuff and production practices. In section 3.2, LCA and TCA are combined to calculate external costs of foodstuff. The sensitivity of LCA and TCA results is challenged in section 3.3. Lastly, we discuss assumptions and limitations, and results of the approach, and draw conclusions both for the level of our findings, and for the implementation of TCA in research practice, and policy in section 4.

2. Material, methods and calculations

Figure 1 illustrates the methodology 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 in examining and comparing environmental benefits or drawbacks of alternative products. As of now, it is also commonly used to evaluate agricultural goods (Poore & Nemecek, 2018). There are several impact assessment methods for LCA. Commonly used in LCA science, and therefore applied in this study, is the method ReCiPe, which evaluates environmental damage (endpoints) in different impact categories (midpoints) (Huijbregts et al., 2017). The herein proposed approach of the combination of LCA and TCA is applied to a case study on foodstuff within this work and builds on preliminary externality assessments (Pieper et al., 2020; Thi et al., 2016).

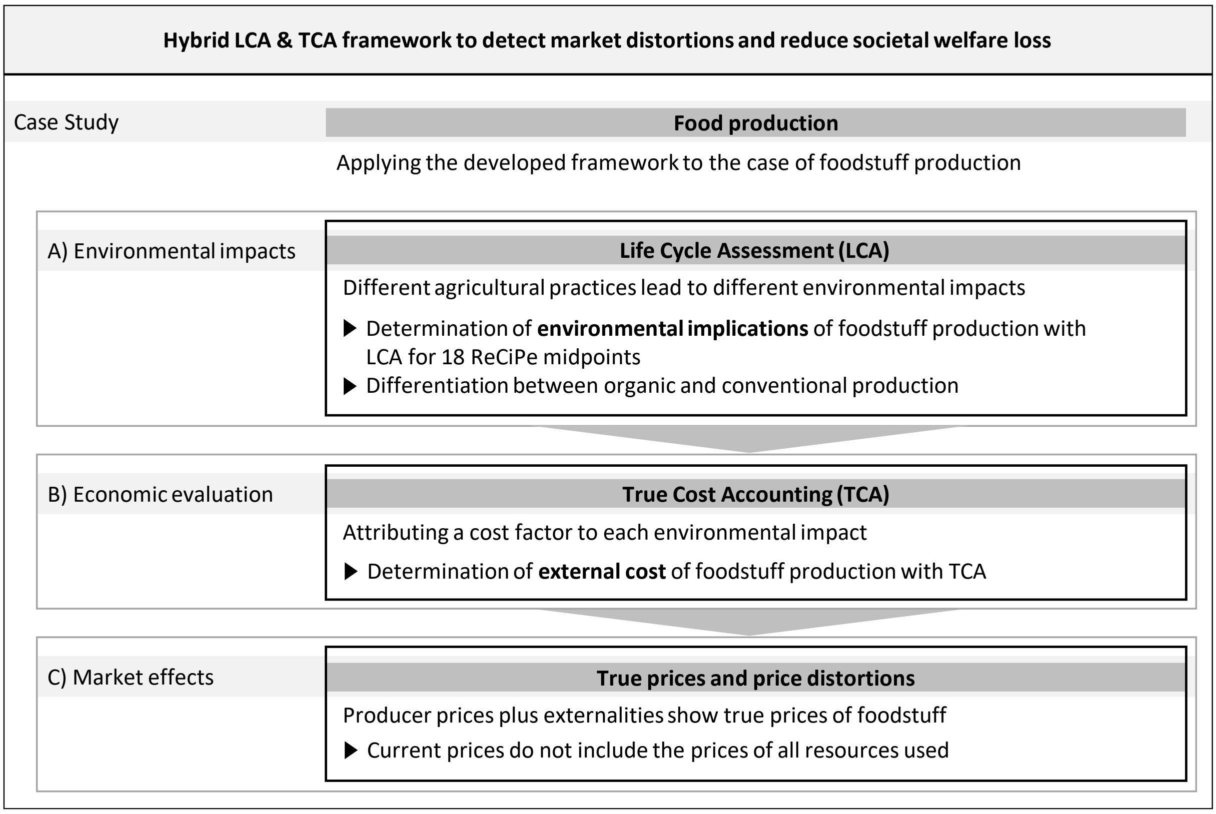

Figure 1: Methodological framework of combined LCA (based on ISO 14040 and 14044) & TCA. In (A), environmental impacts are determined applying the Life Cycle Impact Assessment method ReCiPe 2016 (described in sections 2.1 to 2.3). Section 3.1 presents the LCA results. To evaluate the environmental results monetarily (B), TCA is conducted (described in section 2.3). TCA results are presented in section 3.2. Lastly, (C), we show true prices (as the sum of current producer prices and calculated externalities) and demonstrate how price levels shift with internalized external costs. Within this assessment, the terms “true prices/costs” are used in the context of the used methodology: the calculated externalities are limited to the environmental impacts evaluable

in LCA. These costs therefore cannot represent the fundamentally true value but rather are an approximation of the actual “true prices” of foods.

2.1 Goal and scope definition

The study’s goal is comparative modeling and environmental impact assessment of 22 different products (for an extensive list, see Appendix A1), produced in Germany and assessed per one kilogram 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 foodstuff’s 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 foodstuff production is cradle-to-farmgate in Germany. LCIs from the Agri-Footprint (AFP) 5.0 database (van Paassen et al., 2019) are used for foodstuff production in the conventional base case (cf. Table 1). 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 Inventory

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 A4 and A8. We adjust the inventories of all processes within the system boundaries of the products (see Appendix A9). Upstream processes and pre-products are modelled likewise. In the following details on the inventory adjustments are explained.

2.2.1 Yield, manure, and crop residues, energy consumption, lifespan, and feed intake

This section describes adjustments made to the modeled processes for yield, manure use, energy consumption, livestock lifespan, and feed intake. The respective data is retrieved from the literature analysis.

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.

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 modelling 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 (see Appendix A3) 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). 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. Emissions from crop residues are included with half of each crop’s specific sustainable removal rate (van Paassen et al., 2019). 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 & Wezel, 2017). Due to limited data for specific food groups, we adjust electricity and diesel use for plant-based products (70.6% and 107.8%, respectively) and animal-based products (99.6% and 116.7%, respectively) based on the subordinate food categories (e.g., cereals for wheat, see Appendix A7(c)). 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)). 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).Yield, manure, and crop residues, energy consumption, lifespan, and feed intake

2.2.2 Pesticides, fertilizers, and transport

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 description is provided in Appendices A3 and A9.

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 modelling 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. For the valuation of midpoint results, we focus on categories that contribute at least 2% of impacts to their respective endpoint category for any products or scenarios (for midpoint to endpoint contribution, see Figure S1-4 and table S1-2; for full midpoint and endpoint analysis, see Appendix A4).

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). One method reflecting impacts assessed by ReCiPe is established in the EPH (de Bruyn et al., 2018). 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, 2014b). 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.

2.4 Sensitivity analyses

In this section, uncertainties arising from this framework 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 scenario analysis, which challenges the sensitivity of our results. The conventional base case (C) is defined by the default modeling in AFP 5.0 for each foodstuff. 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 scenario 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.

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 S1-3. The sensitivity analysis is carried out in 3.3.

[1] For *global warming potential*, the price factor is derived from Umweltbundesamt (2020).

[2] For *global warming potential*, the price factor corresponds to the default value given by EPH.

[3] For *global warming potential*, the price factor is derived from Ricke et al. (2018).

Life Cycle Assessment (LCA)		True Cost Accounting (TCA)		Combination of all variations leads to **26** sensitivity analyses (in addition
#	Base cases LCA	#	Base case TCA	
C	Conventional base case	E	Environmental Prices Handbook (EPH), average[1]	
O	Organic base case			
#	Sensitivity analyses LCA	#	Sensitivity analyses TCA	
O1	yield (O) − standard deviation	E1	Environmental Prices Handbook (EPH), lower bound[2]	
O2	yield (O) + standard deviation	E2	Environmental Prices Handbook (EPH), upper bound[3]	
O3	manure (C)	E3	True Price Foundation (TPF)	
O4	manure (literature)			

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 foodstuff category with alternating standard deviations found in literature for all analyzed products in O1 and O2 (see Appendix A7). 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. 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).

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−O5). Further, 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 Results of LCA

Since yield and manure application significantly impact Life Cycle Impact Assessment (LCIA) an analysis of different scenarios is presented in the following. Figure 2 shows the environmental impact of selected organic plant-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 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., lupine, this range is rather pronounced for several midpoints, showing that lupins are highly influenced by their yield and thereby by the impacts of land cultivation per produced kilogram. Ranges of others, e.g., oats, are smaller between the presented scenarios. 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 parameter influencing the results highly is manure application, with higher application rates modelled in O3 and O4 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 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 of foods or in landfills through food waste.

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 Figure 2 for animal-based products is found in the Appendix A4 in Figure S1-5.

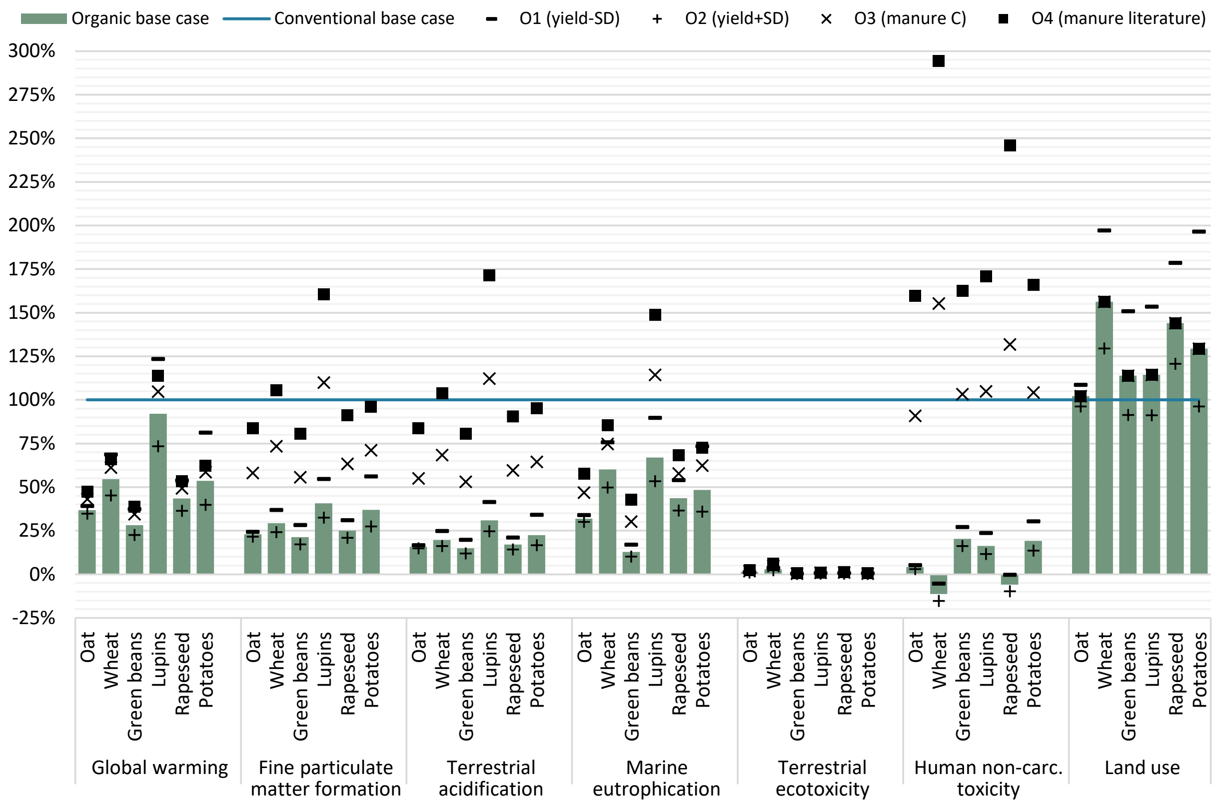

Figure 2: Life Cycle Impact Assessment of organic (O) scenarios focusing on the impact of yield and manure differences compared to the conventional base case (C) as assessed with ReCiPe 2016. For reasons of simplification, figures only include a selection of representative products for each food group 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. An analysis for all plant-based and animal-based products on midpoint and endpoint levels over all scenarios in absolute values is provided in Appendix A4.

Further, 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. Figure 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.

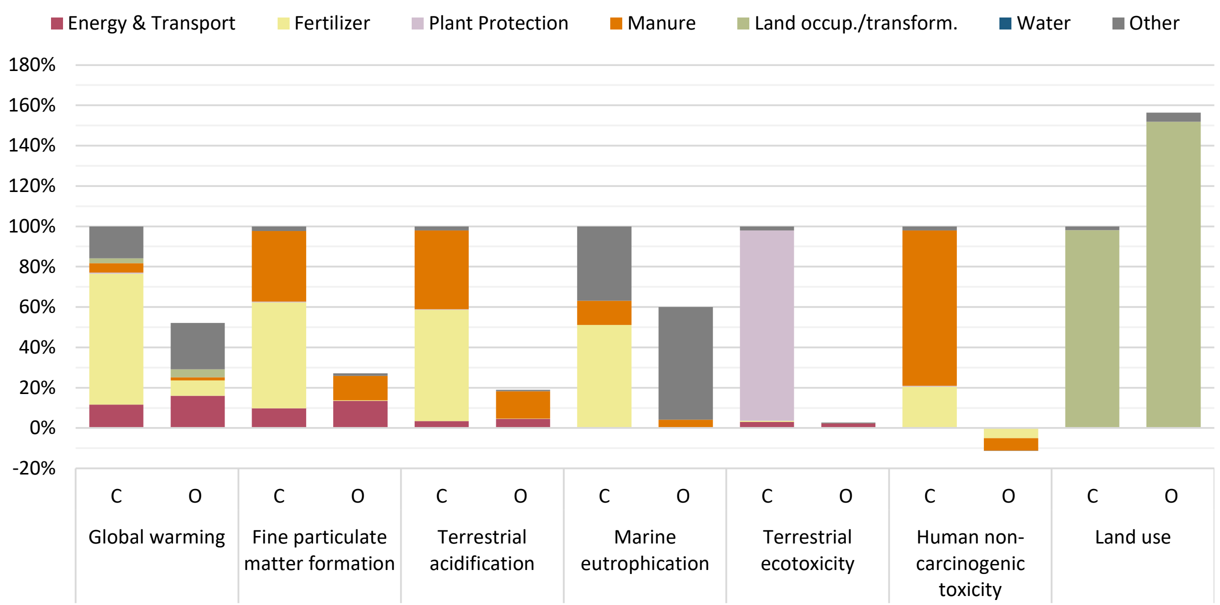

Figure 3: Process contributions for conventional (C) and organic (O) wheat production as assessed with ReCiPe 2016. Processes included in "Energy & Transport" are inputs of diesel fuel on farm site (including associated transports of said fuel), and electricity used in stables. The category "Other" comprises 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.

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 live stage of the animal (cf. system boundaries, Appendix A2). For beef cattle (Figure 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' live 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 with included soil carbon sequestration 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).

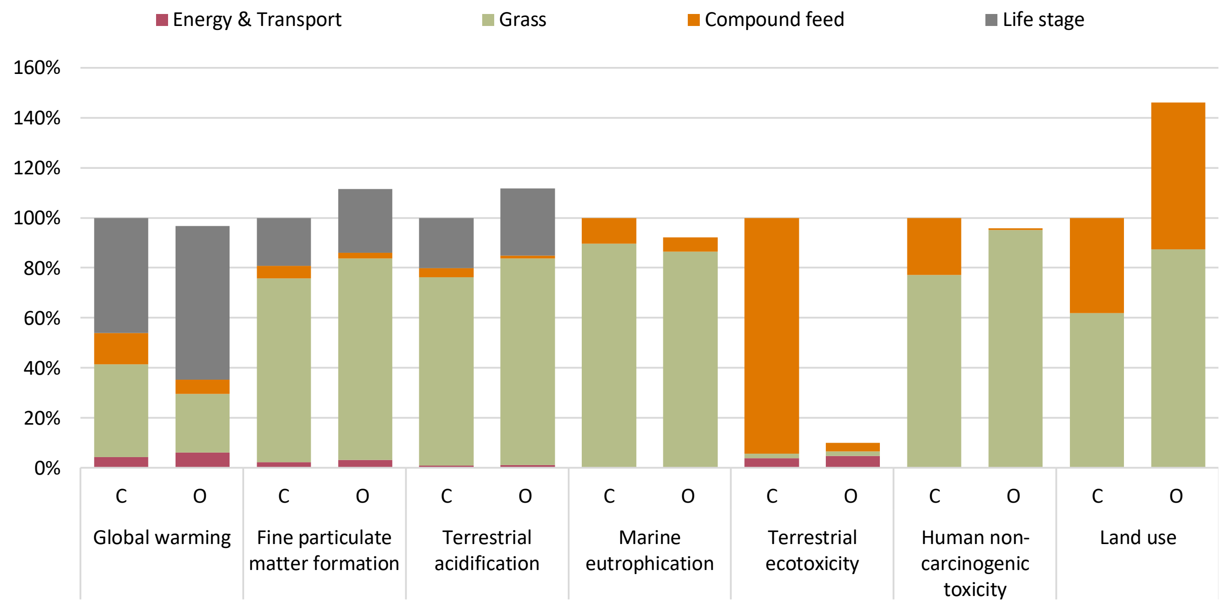

Figure 4: Process contribution for conventional (C) and organic (O) beef cattle production as assessed with ReCiPe 2016. Process contributions for other products (milk, broilers, and eggs) are found in Appendix A4. Processes included in the contribution of "Grass" are application of fertilizers and manure with related emissions (namely N_2O, NH_3, CO_2, NO_3, 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 N_2O and NH_3).

3.2 Results of LCA & TCA

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.

In Figure 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 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.

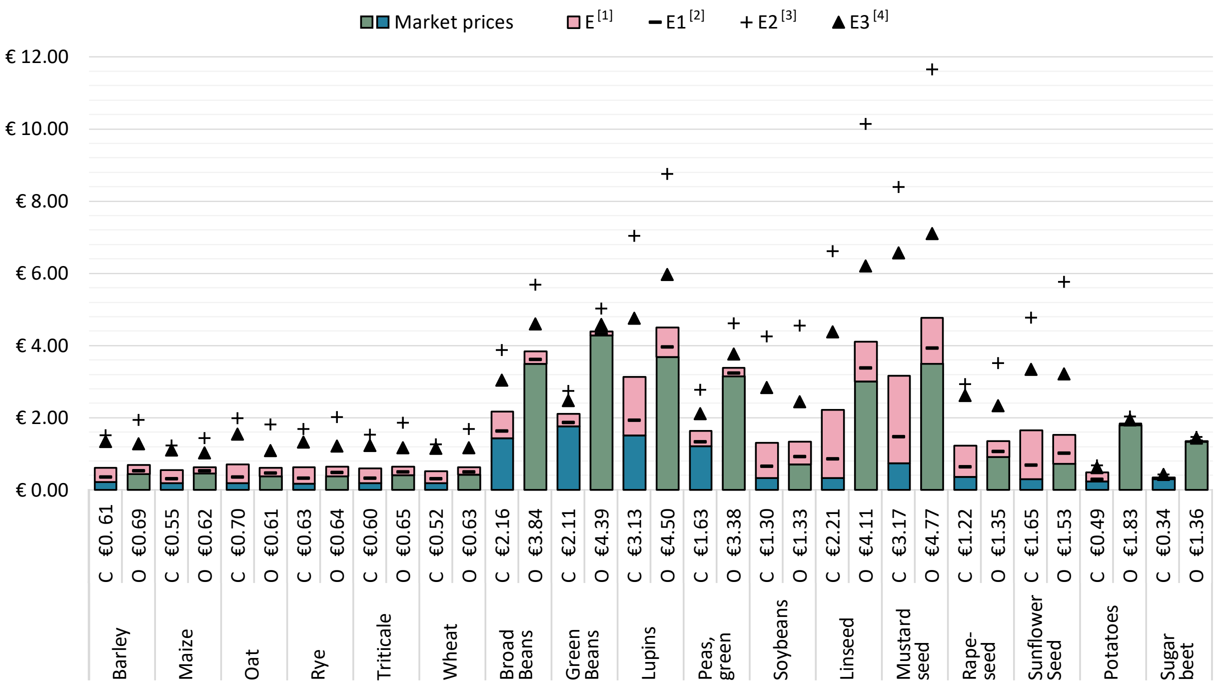

Figure 5: Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) plant-based products in the base case. The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (see [1]). All results shown 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).

In Figure 6, animal-based products are displayed. Market prices differ less strongly than in most plant-based cases. 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%.

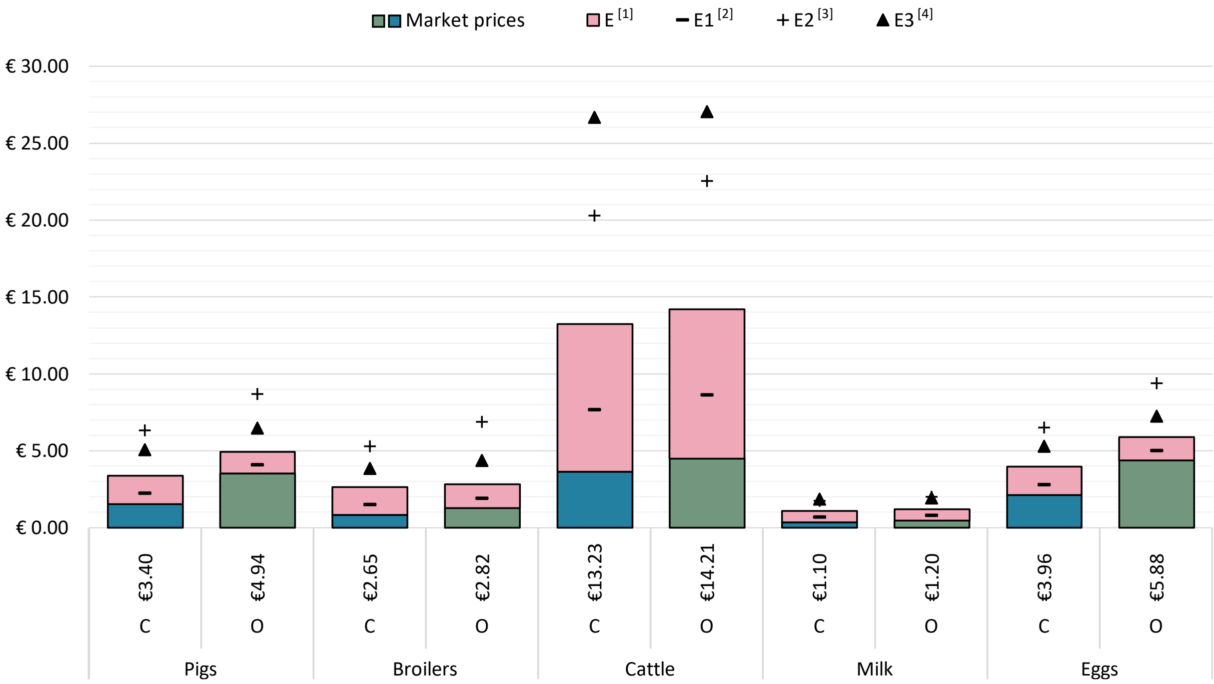

Figure 6: Market prices plus externalities from midpoint valuation for conventional (C) or organic (O) animal-based products in the base case. The costs indicated below the columns represent the market prices and externalities monetized with the base case monetization factor (see [1]). All results shown 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).

3.3 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, Figure 7 shows the range of results for externalities of plant-based products for all possible combinations of scenarios and pricing methods (cf. Table 1).

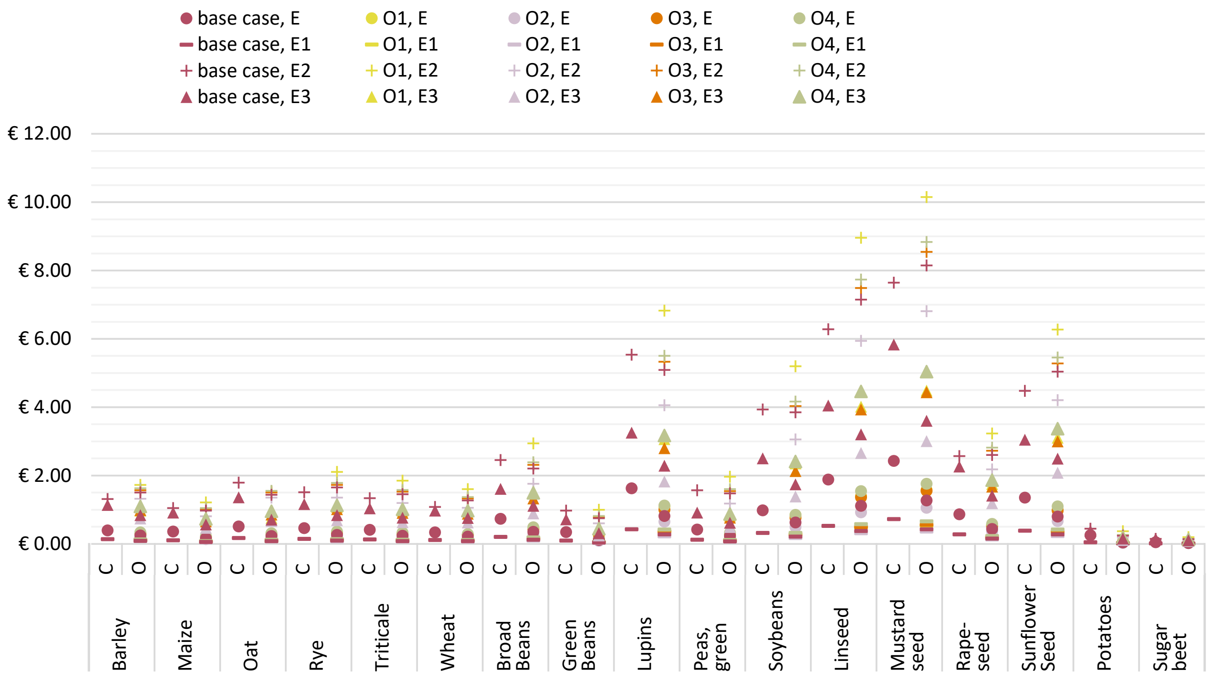

Figure 7: All results shown per kg of product and for the year of 2020. Sensitivity analysis of externalities for conventional (C) or organic (O) plant-based products. The results are differentiated by all possible combinations of the organic base case (O) and scenarios O1−O4 with all pricing methods 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 Figure 5 and Figure 6. Animal-based counterpart can be found in Appendix A6, Figure S-17.

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 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 methods 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.

Another dimension of variability would be an assessment per caloric value. A changed functional unit allows for a better comparison between products, and addresses the conflict between nutritional and environmental aspects, and renders the communication of the results more intricate. Appendix A10 therefore also provides a caloric value of all products (in kilocalories).

4. Discussion and Conclusion

In this study, we assess environmental impacts of organic and conventional foodstuff production in Germany and subsequently monetize impacts to calculate market prices with internalized externalities. We find that on (unweighted) average, plant-based products from conventional production cause externalities of about €0.79, and from organic production of about €0.42 per kg of produce. Conventional meat induces average external costs of €4.42 per kg, organic meat about €4.22 per kg, with beef generating the highest costs of all categories. Animal products from conventional farming induce additional costs of about €1.29 per kg, while organic dairy and eggs cause about €1.10 per kg on average. 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 results highly sensitive towards organic manure application and the yield per hectare or animal, and the underlying monetization method. Therefore, organic production does not perform "better" in terms of true prices, primarily because of lower yields and higher current producer prices, which both offset alleged environmental benefits. Still, an alignment between the prices of both production practices can be noted, especially for cereals, most oilseeds, and most animal-based foods. Besides the addressed uncertainties, results are subject to assumptions and limitations within the LCA and TCA approaches. The temporal system boundaries do not allow to include effects of crop rotation as input factors are assumed to be used for the cultivation of one single crop on the utilized agricultural area. In reality, land is used to cultivate several crops throughout a specific time frame. 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. Further, while we find manure to influence the overall results significantly, manure use is not precisely allocated to each product but generally distributed over the average livestock density per hectare. We want to emphasize that this is a rather theoretical manure modelling approach, which might underestimate results for products produced in livestock-dense regions, where it is likely that more manure is used for production around site. It might in turn 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 only produced on site or in the region, which might underestimate impacts from land transformation that can occur during feed production in other regions. This underestimation, however, is likely to be rather small since it only impacts land use and, to a small extent, global warming (cf. Figure 3). Lastly, regardless of our attempt in using different pricing scenarios, monetizing environmental impact remains highly subjective and thus biased (Ekardt & Henning, 2015; Hansjürgens, 2015). This also includes supposed market effects in terms of lower sales quantities due to price-sales interrelations, which cannot be depicted in this assessment.

Environmentally speaking, the favorability for organic practices is underlined in most cases (cf. Figure 2). Still, according to the calculated true prices, consumers would, in many cases, choose conventional food when optimizing in their economic interest. This is foremost because organic market prices are higher than conventional ones, and alleged environmental favorability compensates for this only in few cases. A current externalities analysis that considers greenhouse gas emissions and land-use change finds very similar notions for conventional and organic foods (Pieper et al., 2020). It must also be noted that beneficial ecosystem services (ES), such as regulating and maintaining soil functions (H. S. Sandhu et al., 2010), are not yet accounted for in LCA and TCA. Since organic production usually leads to lower output of produce but higher ES (Boone et al., 2019) the inclusion of ES in the evaluation of farming practices holds potential for a shift in favor of organic produce. The midpoint of land use, for example, heavily influences the damage to ecosystem quality. Within this midpoint (or endpoint, respectively), the quality of used land is not considered even if this could positively impact the actual ecosystem quality, e.g., with higher biodiversity as is likely in organically treated land (Mueller et al., 2014; Tuck et al., 2014). There are approaches proposed to include ES in common LCA (Alejandre et al., 2019; Rugani et al., 2019; Zhang et al., 2010), but research addresses this in the agricultural context only scarcely (e.g., Boone et al., 2019). Further food analyses need to emphasize the variability of farming systems, which can significantly influence environmental performance as shown in our results. These might be differences in manure handling, or feedstock import. A more thorough emphasis on primary data gathering would render modelling approaches more realistic. Literature argues, for example, that the product-based approach with impacts measures per unit of product generally favors intensive, high yielding practices and underrepresents positive aspects of more gentle approaches (van der Werf et al., 2020). Meng et al. (2017) also find that economic differences derived from lower sales of products due to organic yields are compensated through environmental benefits and savings in farm inputs (due to exclusion of fertilizers or pesticides), and overall show economic advantages in organic production. In addition, alleged economic benefits for organic farmers due to higher profits are scarcely discussed (e.g., Wittwer et al., 2021).

Regardless of the farming or pricing scenarios used for evaluation, plant-based products largely entail lower externalities than animal-based products. These results follow previous findings of foodstuffs' environmental performance and externality assessment (Pieper et al., 2020; Poore & Nemecek, 2018). 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 develop towards a more plant-focused diet, which would be likely with implemented TCA since price increases of animal-based foods would be rather drastic. This dietary transformation would contribute to reaching international sustainability goals and health benefits for consumers (Nelson et al., 2016; Willett et al., 2019).

The high ranges of externalities, as described in section 3.3, have two implications: First, for an adequate assessment of foodstuffs' environmental impact, it is vital to distinguish which production practices and conditions underly the assessed system; second, monetization methods on midpoint level as of now underly 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 does their realization in practice seem, considering, for example, the case of soybeans: the organic market price of €0.70 per kg would be topped off with €3.85 when pricing with E2 and for the organic base case. These results mean a price increase of 547%, which is unlikely to be welcomed by neither producers nor consumers. Nevertheless, it is one possible manifestation of societal costs caused by foodstuff production and must be communicated, even if unpleasant. Hence, a standardization in methods for monetizing externalities is important for successfully setting economic incentives. While the results of section 3.3 show an extensive range in results, products constituting the majority of German production (e.g., cereals, maize, sugar beets, Thorenz et al., 2018), are more stable over all scenarios. We argue that this approach nevertheless indicates the high and manifold externalities borne by societal demand for food, which need to be addressed in economic policy. Currently, natural resources are used for production, for which no prices are paid. Therefore, the formed market price does not contain all relevant information, which leads to a distortion of the market and thereby a loss in social welfare (Sturm & Vogt, 2018).

This study cannot, however, answer the likelihood of putting such prices into action in practice. There have been campaigns of eco-labeling, taxation of GHG emissions, or even the presentation of true prices in supermarkets (Michalke et al., 2020). But consumers' understanding and acceptance of the matter are crucial yet currently lacking (Feucht & Zander, 2018). Furthermore, policymakers need to follow the scientific consensus to advance agricultural systems sustainably.

Lastly, the reflection on agricultural externalities necessitates a discourse on whether the presented approach would result in an abuse of natural capital rather than its conservation and how ethical it is to price the environment: pollution would be allowed to those that can afford it, bringing about another social dimension of the assessed issue. This must be addressed in future socio-political research. Nevertheless, striving for environmentally and socially conscious consumption and production is one important route towards a more sustainable global future. The herein presented approach contributes to the development of economic incentives and policy for sustainable behavior in the food sector.

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Appendix E

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SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainability in Agri-Food Systems: Transformative Trajectories toward the Post-Anthropocene

True cost accounting in agri-food networks: a German case study on informational campaigning and responsible implementation

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Abstract

There is broad scientific consensus that current food systems are neither sustainable nor resilient: many agricultural practices are very resource-intensive and responsible for a large share of global emissions and loss of biodiversity. Consequently, current systems put large pressure on planetary boundaries. According to economic theory, food prices form when there is a balance between supply and demand. Yet, due to the neglect of negative external effects, effective prices are often far from representing the 'true costs'. Current studies show that especially animal-based foodstuff entails vast external costs that currently stay unaccounted for in market prices. Against this background, we explore how informational campaigning on agricultural externalities can contribute to consumer awareness and tolerance of this matter. Further, we investigate the socially just design of monetary incentives and their implementation potentials and challenges. This study builds on the informational campaign of a German supermarket displaying products with two price tags: one of the current market price and the other displaying the 'true' price, which includes several environmental externalities calculated with True Cost Accounting (TCA). Based on interpretations of a consumer survey and a number of expert interviews, in this article we approach the potentials and obstacles of TCA as a communication tool and the challenges of its factual implementation in agri-food networks. Our results show that consumers are generally interested in the topic of true food pricing and would to a certain extent be willing to pay 'true prices' of the inquired foods. However, insufficient transparency and unjust distribution of wealth are feared to bring about communication and social justice concerns in the implementation of TCA. When introducing TCA into current discourse, it is therefore important to develop measures that are socially cautious and backed by relevant legal framework conditions. This poses the chance to create a fair playing ('polluter pays') with a clear assignment of responsibilities to policy makers, and practitioners in addition to customers.

Keywords True Cost Accounting (TCA) · Agri-food networks · Sustainable production and consumption · Food policy · Dietary behavior · Food labeling

Introduction

Established agri-food networks are known to have great potential for increasing their inherent sustainability: ecological damages (like greenhouse gas emissions and telecoupled land-use change) and social issues are putting a strain on the environment and the global community (Campbell et al. 2017). Studies show that current food production exceeds planetary boundaries in the present and future. Presently the agri-food sector constitutes about one-quarter of global emissions (Conijn et al. 2018; Benton et al. 2021; IPCC 2019; Gaugler et al. 2020). However, with a meaningful transformation and combination of measures directed

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towards both production and consumption patterns, agriculture would be able to sustainably feed the global population (Gerten et al. 2020; Springmann et al. 2018; Kennedy et al. 2021).

There has been scientific engagement in manifold approaches, which are not mutually exclusive and should be combined when aiming to transform agri-food networks. One prominent example being quantitative governance measures like cap-and-trade of livestock-related greenhouse gasses (Weishaupt et al. 2020). The rather novel approach of True Cost Accounting (TCA) is another possible measure (Kennedy et al. 2021) and is in accordance with the UN Sustainable Development goals as it describes the Polluter Pays Principle (OECD 1975, UN 2015). Current environmental strains and their associated costs are not accounted for within the market prices of food. Rather, they are paid for by society as a whole, for example with rising prices for clean water (Barraque 2003) or damage done to property through severe weather events (CRED 2019; WRI 2020; IPCC 2019). This represents negative externalities of food production and poses market distortions. When engaging the economic instrument of TCA, ecological and sometimes social implications from agricultural production are monetized and internalized into the price of foods.

Foodstuffs' environmental footprint varies tremendously between different categories of food (Poore and Nemecek 2018). TCA approaches are very sensible when aiming at a calculation of external costs for different kinds of individual foodstuff. This gives consumers and producers the chance to understand the variation in environmental damage from products more deeply and could financially incentivize consumption of sustainable diets, as the inherent external costs of more sustainable production is lower (Gemmill-Herren et al. 2021).

The TCA approach employs the economic thesis that modified price levels on behalf of sustainability actuate consumption behavior change: products that cause high damages would be priced proportionally higher than products that are less harmful; consumers act in their best economic interest and would opt for alternatives with lower associated externalities (Pieper et al. 2020). There previously has been some scientific engagement in the topic of TCA within the assessment of foodstuff. Sandhu et al. (2021), for example, present a framework for a TCA along with farm sustainability metrics. Pieper et al. (2020) calculate external climate costs of different foods while Michalke et al. (2021) assess true food costs based on full life cycle analyses (LCA). Hentschl et al. (2021) specifically look at associated climate and biodiversity costs from land-use change caused by animal-based products. Scientists have recently posed accounting for externalities as one major approach to tackle the biodiversity and climate crisis (Bradshaw et al. 2021) and major organizations, like the Rockefeller Foundation, are engaging in this scientific discourse (Gemmill-Herren et al. 2021). Evidently, a focus on the calculation of such costs is identifiable in current TCA-related research. However, the consideration of consumers when aiming to implement such pricing tools into the market is deficient.

A successful and socially responsible realization of TCA needs to be cognizant of existing inequalities and has to go hand in hand with transparently communicating the underlying issues to consumers, as consumption behavior is a personally and culturally sensitive topic (Stoll-Kleemann and Schmidt 2017; Benka-Coker et al. 2018). Besides the paramount influence of socio-economic and political capabilities, it is important to recognize the effect of individual and socio-cultural factors (Kollmuss and Agyeman 2002) such as awareness, knowledge (Bilharz 2000), values, and attitudes (Schwartz 1977).

Especially today, consumption behavior is closely related to a person's lifestyle and their notion of individual freedom (Kelly et al. 2013; Bobić et al. 2012; Grunert et al. 2001; Pribis et al. 2010). Therefore, awareness for ecological damage in foodstuff production must be fostered in order to achieve a willingness to change consumption patterns (Stoll-Kleemann and O'Riordan 2015; Stoll-Kleemann and Schmidt 2017; Malek et al. 2019) or achieve acceptance to pay for the true prices of food (Yormirzoev et al. 2021). Besides producers and consumers, the realm of globally spun networks, such as agriculture and food systems, is of course also significantly influenced by political actors (Heinrich-Böll-Foundation 2019; Droste et al. 2016). Their legislation can be either conducive or obstructive to the introduction of TCA. Hence, identifying responsibilities for implementation by all stakeholders, policy makers, practitioners, and consumers alike, seems valuable for a successful integration of TCA, which is renowned as an auspicious instrument to sustainably transform current global food markets (Springmann et al. 2017). It will most definitely not solve all issues arising from agricultural production, but nevertheless, it is a purpose-built tool to transparently communicate and ultimately combat current market imperfections at the intersection of planetary health, lifestyle choices of individuals, and world economics.

TCA implementation is dispersed globally. Within regions of the Global South, the topic is primarily being promoted at farm level or through cooperatives rather than with standardized economic frameworks. Within the European context, heterogeneities in development persist as well: while the Netherlands is considered a TCA frontrunner with plenty of initiatives and pilot projects, German networks are still regionally or topically limited and have the potential for growth. To bring this sustainability endeavor to the attention of German political decision-makers and consumers alike, a German supermarket chain started an informational campaign displaying second price tags based on TCA calculations from Michalke et al. (2020) in its store 'Grüner Weg' ('Green Way') in Berlin. Besides the normal market price, some products were also labeled with their 'true prices'. The campaign is meant to purely inform customers about the hidden ecological costs of food, rather than to implement TCA as an economic instrument (cf. Sect. 2.2).

On the basis of the 'True Prices' campaign, this paper analyzes the consumers' knowledge of external costs of foodstuff and the campaign's potential for broadening it. Further, the campaign's design-related flaws, as well as underlying methodological obstacles, are explored. Customers' potential behavioral change after a hypothetical implementation of TCA is also addressed. Finally, we explore different stakeholders' responsibility for, and social issues connected with, an actual implementation of TCA in the foodstuff sector. Answering these questions is pursued with a customer survey (cf. 2.3) and expert interviews (cf. 2.4). This work aims to identify obstacles and potentials for introducing TCA of food as an informational tool, calculation framework, and as an actual economic intervention to consumers, practice, and policies.

Methods and materials

In the following, we will first elaborate on the study's design and research procedure. We will then explain the 'True Prices' campaign, which the subsequently described consumer survey assesses and the expert interviews are based upon.

Framework

Figure 1 illustrates the framework design we follow in this study. The scientific background of Michalke et al. (2020) and its application in the 'True Prices' campaign build the foundation for this case study. First, a description of the employed method to calculate ecological costs of foodstuff can be found in Sect. 2.2. Results of this calculation were used to present 'true price' tags (cf. Fig. 1) in the market and showcase more information on the context of ecological costs of foods. On the basis of the 'True Prices' campaign, we conducted quantitative research on the consumers' perception of TCA, and experts' evaluations of TCA research and measures. The face-to-face consumer survey is described in 2.3, the expert interviews, which build the background of our qualitative assessments, are described in 2.4. The respective results are presented in Sect. 3, with Sets. 3.1–3.4 mainly focusing on the quantitative assessments with selective augmentation through the experts' assertions, which are then emphasized in Sect. 3.5. Conclusions for the politically successful and socially compatible implementation of further TCA campaigns can be drawn from the combination of both perspectives (cf. 4 and 5).

'True Prices' campaign

The following section introduces the informational campaign which uses 'true price tags' to emphasize the context of ecological damages in food production and (in case of their internalization) its effects on the products' prices.

In this paper, the term 'true price / cost' is and will be used according to the calculations by Michalke et al. (2020) and the resulting campaign. However, we want to emphasize that their calculation does not aim to reflect the full extent of all existing social and environmental externalities. For one, the basis for monetary evaluation is currently limited to selected ecological parameters, and most approaches entirely neglect the calculation of social costs. This is due to a lack of data availability and highly complex issues underlying most social externalities. Furthermore, it is important to acknowledge the general limitations of economically assessing complex, non-human systems: valuation will always be instrumental (ethically subjective, anthropocentric) and thus partial (Ekardt 2015; Hansjürgens 2015). Therefore, some scholars argue that in its worst manifestation, TCA is not an all around cure to transform current agricultural market structures but plays into prevailing neo-liberalism by merely 'green coloring' i.e monetarily valuing nature or social justice in a way that uphold the same structures that have caused and are causing environmental and social damage in the first place (Patel 2021; de Adelhart Toorop 2021). Nonetheless, other TCA practitioners and scholars argue that, in light of the factual devaluation taking place, the economisation of (ecological) damage is not only admissible but can provide—if pragmatically assessed and intelligently applied—valuable means for communication and comparability (TEEB 2018; Pieper et al. 2020; Baker et al. 2020; Bradshaw et al. 2021).

Michalke et al. (2020) assess environmental externalities of eight different foods (apples, potatoes, tomatoes, bananas, mozzarella cheese, gouda cheese, milk, and mixed minced meat) based on data from the Federal Environmental Agency of Germany (UBA 2020). The damages included in the assessment are costs from greenhouse gas (GHG) emissions, reactive nitrogen (N_r) emissions, energy consumption, and GHG emissions related to land-use change (LUC). These externalities are only parts of the full 'true costs' caused by agricultural practices. Other environmental issues related to food production are, for example, the use of pesticides or water use. Further, social issues related to agricultural production are barely scratched within the context of land-use change (and with it the imposed threat to the human habitat of mostly indigenous peoples) and remain mostly unassessed.

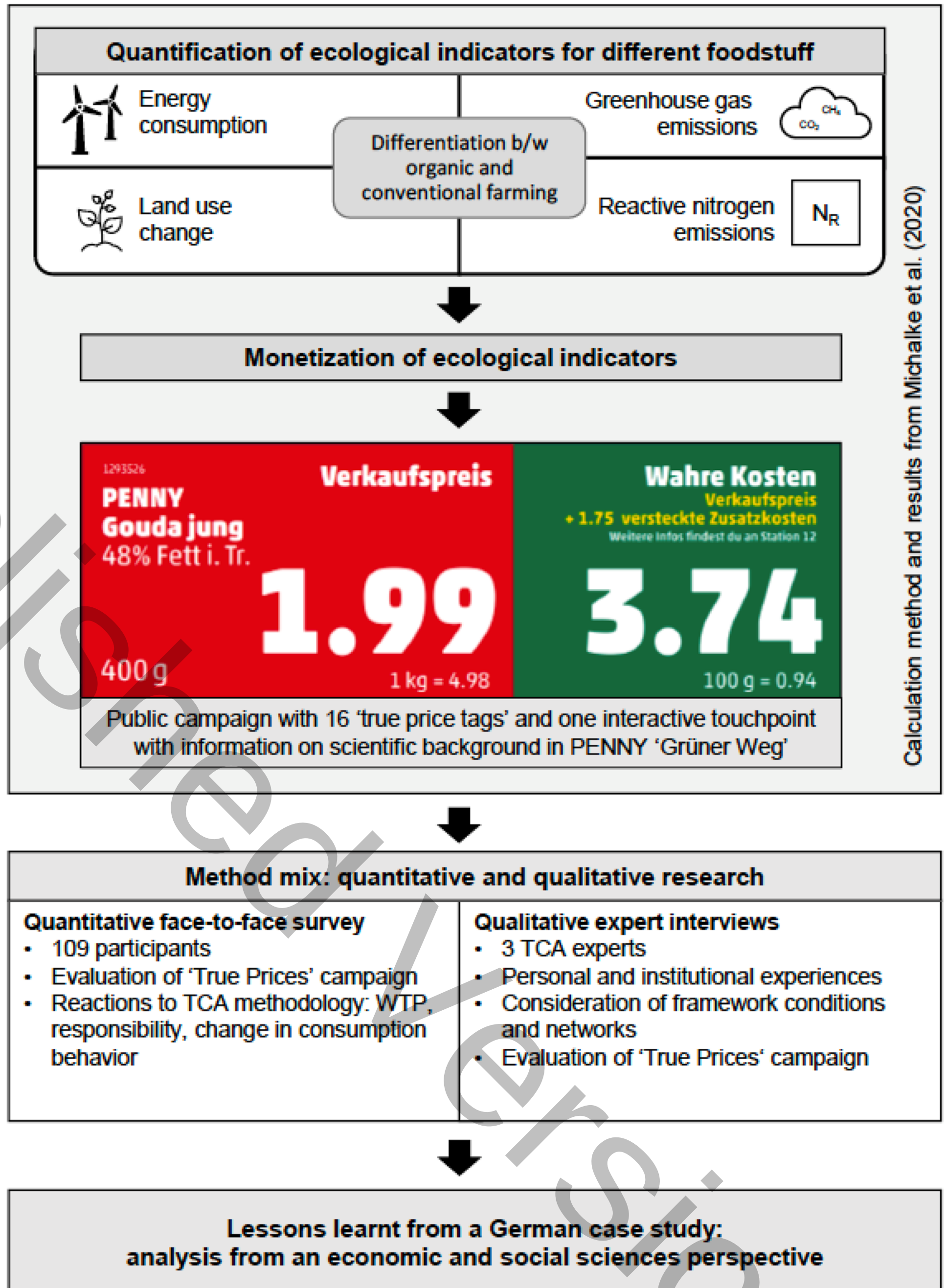

Fig. 1 Framework design with quantitative and qualitative empirical research based on the 'True Prices' campaign elaborated in Michalke et al. (2020)

Within the assessment of Michalke et al. (2020), a differentiation was made between different foods as well as between distinct production practices. Each product was assessed when produced under conventional and organic conditions. Under different regulations and conditions, production inputs will vary. For example, in organic production artificial nitrogen fertilizer is only allowed to a very limited extent (European Union 2008), which impacts nitrogen emissions released during the production process. The differentiation was made based on a literature analysis of studies comparing the two production practices. The system boundaries are defined as cradle-to-gate, meaning that all pre-production (like production of fertilizers, feed, seeds, etc.), production at the farm stage, as well as processing after the farm stage were included in the externality assessment. Emissions occurring in the supermarket, during transport to, or through processing in the home of consumers are not included. The monetization of damages was based on data from cost–benefit-analyses from the Federal Environmental Agency (for GHG and energy consumption; UBA 2019) and the European Nitrogen Assessment (for N_r; Sutton et al. 2011).

Table 1 External costs from GHG and N_r emissions, energy consumption, and LUC related GHG emissions from Michalke et al. (2020)

Product	Organic [€ / kg product]	Conventional [€ / kg product]
Apple	0.12	0.17
Tomato	0.20	0.18
Potato	0.07	0.07
Banana	0.15	0.20
Mozzarella	2.14	2.84
Gouda	3.26	4.38
Milk	0.75	0.89
Minced meat[a]	11.58	9.67

Costs are presented per kg of product. These costs do not include the current market price, but solely reflect external costs.

[a]The minced meat consists of a mix between pork and beef as commonly sold in German supermarkets. In the text, we refer to it as minced meat.

External costs were calculated with the described methods and data for every product mentioned. These costs (cf. Table 1) were then added to the current market prices by the supermarket operators themselves: price tags were printed with not only the market prices at which products are sold presently but also with the 'true prices' as calculated by Michalke et al. (2020). These price tags were used for informational purposes only. This was because customers were not actually able to pay for the 'true prices' at checkout. There is also the possibility in store to find out more about the context of agricultural externalities via an interactive information point where customers can, for example, guess the 'true costs' of a certain product.

Quantitative survey

As aforementioned, the TCA calculations by Michalke et al. (2020; cf. 2.2) were used in a supermarket informational campaign in a German discounter in Berlin. The survey's main focus is to evaluate this campaign, and with it the participants' general knowledge of ecological costs caused by the agri-food industry. Further, we aimed to obtain an estimate of the general societal attitude and expectations towards TCA and its implementation.

A quantitative face-to-face survey of medium length (duration 7–10 min) was designed (Stocké 2014). The standardized questionnaire (Reinecke 2014) was carried out via the tool SoSci Survey. SPSS was used for the statistical analysis of the collected data. The survey was divided into different sections. First, consumers were asked about their general purchasing behavior and their familiarity with the campaign. Only after such first questions did the interviewers explain the background of the campaign to participants. They were then asked for their perception of the campaign as well as their willingness to pay for the 'true prices' of different products. Furthermore, information was collected on which factors of ecological or social impact should be internalized in true pricing and whom of government, economic sector, or general public the respondents deem responsible for initiating TCA. Assuming TCA would be implemented, consumers were questioned on whether they would change their consumption intake regarding organic and animal-based products. Finally, selected socio-demographic data of participants was collected to evaluate the composition of the sample.

The collected sociodemographic data regarding age, household, and budget for grocery presented in the sample (109 participants) to be fairly representative for German society as a whole (cf. Table 2). 66% female ($N=72$) and 34% ($N=37$) male customers participated in the survey. Gender-specific differences in grocery purchase behavior and pro-environmental behavior, in general, are often discussed (Bandura et al. 1996; Borden and Francis 1978; Dietz et al. 2002). However, in this particular survey, we focused on households as a unit and, therefore, gender-specific conclusions are inadmissible.

Table 2 Structure of survey participants

	Survey participants ($n=109$)	German population (average)
Age [years]		
Mean	45.05	46.51[a]
Min	14	n/a
Max	86	n/a
Gender [%]		
Female	66	50.7[b]
Male	34	49.3[b]
Household size [persons/household]		
Mean	2.29	2.03[c]
Min	1	n/a
Max	8	n/a
Monthly budget grocery [€/household]		
Mean	360.64	321[d]
Min	15	n/a
Max	1500	n/a

[a]Federal Institute for Population Research (2019)

[b]Federal Statistical Office (2021a)

[c]Federal Statistical Office (2021b)

[d]Federal Statistical Office (2021c)

Qualitative interviews

Following the quantitative survey and campaign evaluation, three expert interviews with TCA practitioners were conducted. These interviews were executed to validate and complement perceptions and ideas of consumers. Further, the interviewees were encouraged to share their expertise on potentials and obstacles for introducing TCA approaches today and in the future.

These interviews followed a predesigned interview guideline with the possibility for further ad-hoc questions and discussion (Baur and Blasius 2014) and were evaluated according to the rules of qualitative content analysis (Mayring and Fenzl 2014). Topical sections were, first, the experts' business involvement in TCA and their perception of acceptance and interest on the market, putting a focus on their personal and institutional experiences. Afterwards, they were asked about chances and risks regarding the implementation of TCA with regard to the political and administrative environment. Finally, their assessment of the 'True Prices' campaign and selected takeaways from the consumer survey were discussed. The three interviews took approximately 60 min each and were conducted via recorded video call. For analysis, video-cued thought protocols were engaged, and important excerpts were summarized.

Experts from three different TCA perspectives were consulted for the research. The first interview partner was a representative of 'Eosta' (abbreviated to "EO" in the following). Eosta is committed to the implementation of TCA and acts as a global distributor specializing in organic fruit and vegetables with a focus on greenhouse cultivation and overseas fruits. A representative of 'Truesday' (abbreviated to "TD" in the following), a TCA specialty coffee brand residing in Berlin, which is selling the first German true price coffee, was selected as the second expert. A TCA consultant with 'Soil & More Impacts' (abbreviated to "SI" in the following), acted as the third expert. Soil & More Impacts identifies and monetizes costs and benefits of agriculture with a focus on soil, climate, water, and biodiversity. Their target groups include i.a. the agri-food and financial sectors, policy makers, and consumers.

Results

We present the results of both the customer survey and experts' evaluation in the following. With these results, we want to specifically focus on the general knowledge of consumers about TCA and the communication of the approach both within the campaign and in general. We further investigate customers' reaction if TCA were to be broadly introduced to the market and the perceived responsibility of different stakeholders for a socially just implementation.

Consumers' knowledge of ecological costs

In the first part of the survey, we aimed to explore whether customers are generally aware of (ecological) externalities. Out of 109 participants in the standardized face-to-face survey, a total of 56% ($N=61$) did notice the price tags and/or the infopoint, which constituted the 'True Prices' informational campaign. Even though over half of the participants did see the price tags, they did not necessarily know their meaning nor were able to explain the price increase and calculation indicators. Only 10.09% ($N=11$) were able to name one or several reasons for the increased price [indicated ecological damages, as calculated based on Michalke et al. (2020)]. Additionally, a further 20.18% ($N=22$) expected different social factors to be the reason for the price increase displayed by the 'true price' tags. Mentioned factors as such were, for example, animal welfare, fair wages for workers in the production sector, and production costs (however, these aspects were neither included in the calculations nor displayed at the information point in the market).

Regarding the participants' general knowledge of the topic, 77.1% ($N=84$) had heard of the true prices of food and its underlying issues before. Most of the participants (41.3%, $N=45$) received the information via media (TV, radio, newspaper). Ten people (9.2%) actually stated that they were made aware of the existing problems through the 'True Prices' campaign itself. Other sources of information mentioned by respondents were social media ($N=7$), friends and family ($N=7$), farmers' lobby ($N=4$), or climate activist groups ($N=3$).

These findings on consumers' general perception of the campaign indicate a knowledge gap for ecological costs in foodstuff production and agri-food networks within the sample. The interviewed TCA practitioners agree with a presumed knowledge deficit (SI, EO), stating that while the consumers' interest is promising for a successful and accepted implementation of TCA, their level of knowledge still seems insufficient to motivate extensive changes in consumption behavior (EO, TD).

Campaign communication

Further, we investigated if informational campaigns, such as the one presented here, can create awareness for ecological issues in current agri-food systems. We were also interested in the campaign's design-related flaws. A majority of 63.3% ($N=69$) assessed the campaign and its message as 'good / interesting'. On the other hand, 14.7% ($N=16$) rated it as 'pointless / superfluous' or were 'skeptical' (12.8%, $N=14$) about it. Findings from the consumer survey show some potential to increase efforts in presentation, explanation, and structuring for future campaigns. As described in 3.1, participants showed very little basic understanding of context, despite the fact that a majority had heard of the topic before, and presumed other issues underlying the 'true prices' than those actually addressed in the campaign. Furthermore, some participants were confused over the color coding of price tags (for reference, cf. Fig. 1) and assumed the price tags' green part to signify organic produce (2.75%, N = 3), and/or the red part to display a product on discount (8.25%, N = 9).

The three experts collectively agree that public campaigns signify great potential towards raising awareness for negative externalities as they utilize TCA as a method to transparently communicate ecological damage to the general public. The Eosta representative (EO) highlights the need for a mindshift and raised levels of awareness of the current unsustainability in agri-food networks as fundamental to introducing TCA as an accepted accounting practice. Truesday Coffee (TD) suggests complementation knowledge-focused measures with tangible offers to take immediate action. This ties in with the statements of two participants who suggested that consumers should indeed have the opportunity to pay the true price voluntarily. TCAs methodological strength lies in addressing these crucial challenges through the holistic integration of people and planet, and thus holds great potential in improving the currently unsustainable agri-food networks (SI, EO, TD).

Monetary factors influencing consumption behavior

Regarding TCAs influence on consumers' behavior, we focused on estimating the customers' willingness to pay for 'true prices' and how the implementation of TCA adjusted pricing would possibly change consumption habits. Assuming that an implementation of the TCA methodology will raise food prices, participants were asked about their willingness to pay (WTP) for product prices with internalized ecological costs. WTP is defined as the maximum price at or below which a customer will definitely buy a product (Tisdell 2005).

To determine the WTP in the survey, three conventionally produced products with their calculated true cost price tag were presented to the customers. Different product categories were included, one plant-based food item (apples) and two animal products: gouda cheese (dairy) and minced meat. Participants were asked whether they would be willing to pay the corresponding 'true price' for the respective product or, if not, how much they would maximally be willing to pay. The price increases in the Penny supermarket are composed as follows (cf. Table 1): four medium-sized apples (500 g) entail additional negative externalities of 0.09 €, one package of gouda cheese (400 g) comprises a surplus of 1.75 €, and for 500 g minced meat an additional cost of 4.83 € was determined.

Most respondents (94.5%, *N* = 103) were willing to pay the 'true price' for the apples. A little less than half of the participants (43.9%, *N* = 47) agreed to pay the 'true price' for the gouda cheese. WTP for minced meat was lowest with 33.7% (*N* = 35) of participants consenting to cover the surplus entirely. Comparing the three selected products and their WTP data, it is apparent that customers were least willing to pay for the most expensive product (which also includes the highest negative externalities).

Provided the participants rejected paying the 'true price' ('if not'), their maximum WTP was subsequently inquired. This was done to get more detailed answers on socially accepted increases in food prices. As shown in Fig. 2, the maximum WTP for gouda was, in relation to the current market price, higher than for minced meat. On average, those refusing to cover the 'true price' were willing to pay approx. 29% of the price increase for minced meat, which corresponds to a value of 1.41 €. For the gouda cheese, the value

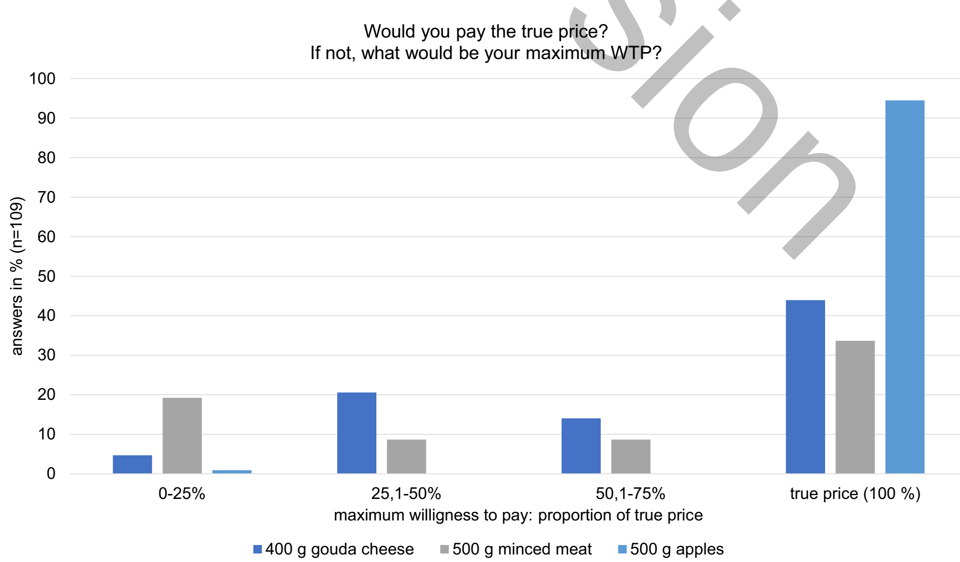

Fig. 2 Relative frequencies of given answers to the questions "Would you pay the following price increase for the true cost of these products?". If the previous answer was "no": "What would be your maximum willingness to pay?". N = 109

is slightly higher: the participants were on average willing to pay approx. 38% of the calculated negative externalities. This resembles a monetary value of 0.66 €. Comparing the collected WTP data, less acceptance for drastic price increases of products can be observed.

Another focus of the study was to explore potential changes in consumption behavior. As described, participants had already been informed about the general methodology of TCA for food and the underlying calculation base (cf. 3.3). Therefore, a general understanding of why prices would be higher with TCA could be attested when inquiring about potential consumption changes. To measure the possible effects of true pricing on consumer behavior, questions focused on changes in consumption of organic and animal-based products.

First, we will give some perspective on the price design of organic and conventional products, respectively. In most cases, the calculated externalities of organic produce are lower than those of conventional produce (except for tomatoes and minced meat, cf. Table 1). Therefore, the price of organic foods would rise less sharply when implementing TCA. As of now, organic products generally have higher market prices than their conventional conspecifics, TCA implementation would diminish these market price differences in favor of organic products; thus making organic products more attractive to consumers not only on an ideological, but also financial basis. Consequently, when consumers were asked if an implementation of TCA for foodstuff would lead them to opt for more organic produce, the following results were yielded: 76.1% ($N=83$) of respondents stated that they would increasingly resort to organic products compared to their current shopping behavior. 23% ($N=25$) replied they would not buy more organic products than they do now. The answer 'no' was further elaborated in a subsequent open question with the following replies: doubts about the organic label (64%, $N=14$), already a lot of organic products (18%, $N=4$), daily quality more important (9%, $N=2$), brands instead of the organic label (5%, $N=1$), and favor of regional products (5%, $N=1$).

Second, we examined the possibility of behavior change regarding animal products (cf. Fig. 3). Based on the calculations of Michalke et al. (2021), animal-based foods entail significantly higher negative externalities than plant-based products (cf. Table 1). 60.6% ($N=66$) of participants stated they would reduce their consumption of animal products if the previously explained true pricing was implemented. People who answered in the negative (39%, $N=43$) gave the following reasons: already reduced consumption compared to previous eating habits (45%, $N=17$), taste preference (24%, $N=9$), (family) eating habits (15%, $N=6$), no present consumption (8%, $N=3$), and ability to pay (5%, $N=2$).

Overall, it can be stated that consumers generally would be willing to change their behavior to a certain extent, if positive or negative monetary incentives were created through the implementation of TCA for food. More than 75% ($N=83$) of participants would increase their consumption of organic products in particular. The data from this case study also demonstrates that the consumption of animal products has the potential to be reduced considerably: more than 60% ($N=66$) of respondents stated that a comprehensive implementation of 'true prices' would lead them to reduce their consumption of animal-based products.

Responsibility for implementation

The last focus of the survey was assessing the perceived responsibility for TCA and its modes of implementation to transform currently unsustainable agri-food networks. Here, the consumers' perspective on the importance of TCA in

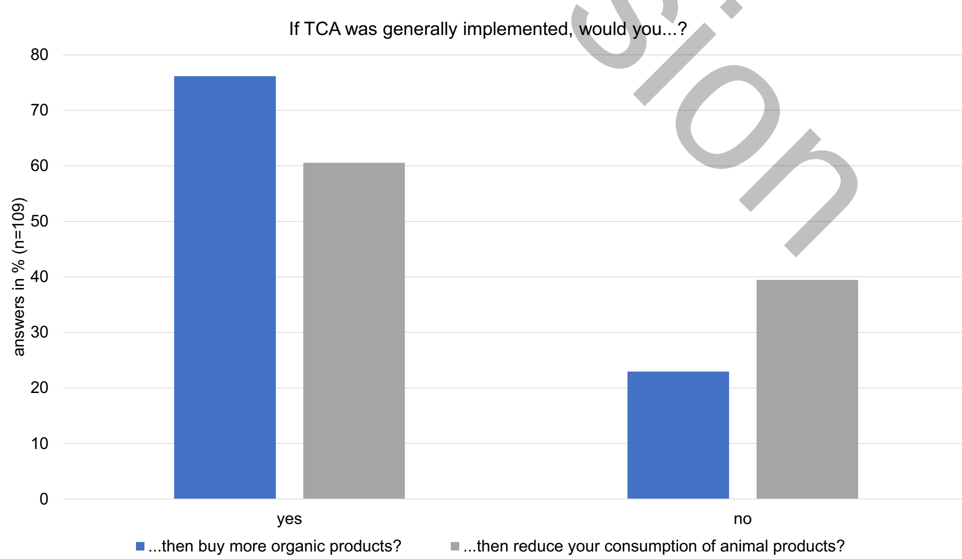

Fig. 3 Relative answers to the questions "If TCA was generally implemented…": **a** "…would you then buy more organic products?" and **b** "…would you then reduce your consumption of animal products?". $N=109$

general and stakeholder responsibility for the implementation of 'true prices' was explored.

To attain broad acceptance, it is important to validate which aspects of TCA approaches are especially valued by the general public. Hence, we asked participants ($N=109$) which of the following factors would be most important to be included in TCA: ecological, social or animal welfare (maximum two selections permitted). Alternatively, the options of 'all of the aforementioned' or 'no increase in market prices' were given. The results reinforce the self-prescribed necessity for holistic assessment in TCA. 69.8% ($N=64$) replied that all factors were equally important for consideration. The wish for conceptual inclusivity is further highlighted as both social factors (20.7%, $N=19$) and animal welfare (30.5%, $N=28$) received more single mentions than ecological factors (16.4%, $N=15$). Three people (3.3%) opted for 'no price increase' as primarily important.

The general need for TCA is a widely shared view. Amongst the participants ($N=109$), a large majority of over 90% ascribed importance to implementing TCA. 51.4% ($N=56$) stated this endeavor to be 'very important' a further 41.3% ($N=45$) selected the option 'rather important', and only two people (1.8%) deemed it to be 'not important at all'.

As TCA is a relatively new tool, it is still largely pushed by individual actors and networks (cf. 4). Three mutually inclusive pathways for a transformation of agri-food systems through TCA are possible: motivated by the government through policies, the economic sector through responsible production, and the general public through conscious consumption. Each could potentially be viewed as liable to translate this novel method into the common application. We, therefore, asked the participants ($N=107$) which of the three actors they deem responsible. They were asked to rank the government, economic sector, and general public in terms of their perceived duty to implement sustainable food production and consumption practices. At least one rank had to be selected. Alternatively, they could opt for "all actors equally responsible".

As seen in Fig. 4, the majority of participants (54.2%; $N=58$) view the government, or policy makers, as foremost responsible in implementing more sustainable practices into agri-food networks (rank 1). Another 18.7% ($N=20$) voted for the option 'all actors equally'. The general public was voted foremost in charge by 17.8% ($N=19$), while the economic sector received 9.4% ($N=10$) of votes. The latter was, however, most often defined as second rank responsible with 21.5% ($N=23$). To get an overview, overall mentions of each actor are interesting as well. While the government was by far the most mentioned ($N=72$) over all ranks, the general public came second ($N=50$), and the economic sector was in third place ($N=44$). This indicates that consumers do see the necessity of policy makers to act according to current needs for sustainability.

Pathways for implementation

Throughout the survey, questions regarding responsibility for implementation and ways of implementation arose which are addressed here. In the qualitative expert interviews, key challenges that await clarification prior to a successful application of TCA were of interest. Furthermore, we inquired what would be effective means, incentives, and framework conditions to successfully engage TCA in practice.

To realize the potential inherent to TCA approaches abundant methodological finetuning is needed (SI, TD). To remove obstacles regarding customer approval and comparability, it is important to anticipate critical feedback prior to introducing the method as a general intervention to markets, claims Soil & More Impacts, explaining that TCA needs to meet the self-prescribed demand of holistic assessment

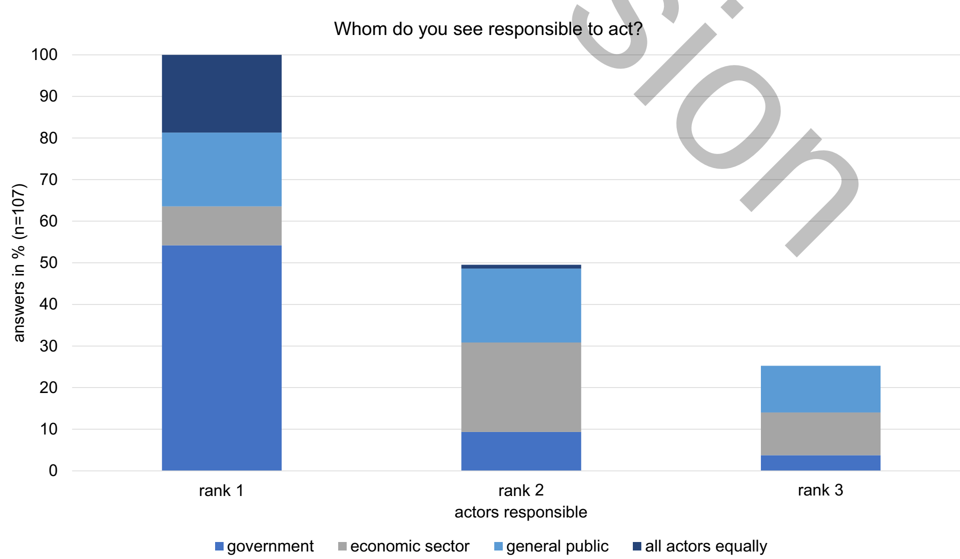

Fig. 4 Relative frequencies of given answers to the question "Whom do you see responsible to act?". $N=107$

across all forms of capital. Fields for further refinement are general preciseness and the calculation of animal-based products which still prove to be problematic in confident calculations (SI). Specificities in production practices, such as distinctly accounting for certified products (e.g., organic, fairtrade), need further development (TD, EO), and with respect to a persisting lack of consumers' trust and knowledge, proper communicating is needed (cf. 3.1).

A clear scientific consensus for a uniform approach moving forward is yet to be reached (cf. 4.1). As of now, existing TCA methods fall short of aspired levels of holistic accounting but are foreseen to be adequately developed to meet the level of accuracy required for proper transparency (SI, TD). Although it remains challenging to combine planetary and societal sustainability with existing data gaps, this is perceived as a clear strength of TCA: approaches exceed interventions with a singular focus on climate and emissions by integrating diverse ecological indicators, e.g., as addressed in the Planetary Boundaries framework (SI, EO).

To realize the full potential inherent to TCA, a sensible integration of social and ecological dimensions, and herein entailed sensitive data differences needs to be accomplished (EO, SI,TD). One fundamental question yet to be clarified is considering the technical approach to compare and possibly offset natural, human, and social capital (SI). There are manifold approaches to do this (e.g. secondary or primary data approach) and a standardization is not yet underway, which would arguably be beneficial for the consumers' acceptance. Literature also shows that whichever approach is used for the calculation of true prices, it needs to be comprehensible and transparent for the target group the respective calculation is aimed at (Gemmill-Herren et al. 2021).

While discussing the further pathways for implementation of TCA across all stakeholders (public society, government, and economy), Truesday suggests a TCA label as an adequate step towards improving TCA standards and reputation, while Soil & More Impacts reiterates the central importance of engaging the Polluter Pays Principle: Hastily introducing a TCA label could insufficiently place the customer into the main focus of being responsible for implementation, whilst diminishing the producing actors' role in achieving higher levels of sustainability in agri-food networks. This ties with concerns of TCA measures adding to social injustice while failing to combat the prevailing market distortions in true ecological and social pricing, which are to be tackled by policy makers alike.

In the interviews, experts focused on the productive potential of political action ahead: TCA's imminent strength in holistically integrating societal and planetary issues suitably addresses the sustainability endeavors that global politics claim to strive towards (SI, TD, EO). Hence, an extensive implementation of TCA pursued by the legislature of all states (at least in the Global North) seems to be the logical step forward. A number of established instruments and frameworks exist (such as subsidiary practice, CO_2-Pricing, and taxation) that would profit from employing TCA, as elaborated by the experts. Such integration of true pricing pre-consumer stage seems favorable with respect to social implications and general leverage for systemic transformation.

Crucial traits for successful development are listed as follows: an active exchange between all players, administrative support, public promotion, and ultimately a formalization of TCA structures. Outside reactions to TCA on business levels vary greatly, all experts agree. TCA is already viewed as a veritable assessment tool for transparency in supply chains, communication, and comparison. On the corporate side, TCA seems to be gaining increased standing, as the food industry recognizes the need for a uniform measurement tool regarding ecological costs (SI). While more and more companies understand TCA as a possibility for profit through frontrunning and thus show interest in engaging in these contexts through adapting their business approaches regarding socio-ecological responsibilities, other players on the market view TCA with skepticism and behave in a wait-and-see manner (SI, TD, EO).

The experts highlight the inherent theory of change: through monetization, TCA is 'speaking the language' of financial markets. By internalizing all costs (social, ecological) into the definition of profit it poses a powerful tool to realize the Polluter Pays Principle. Thus, TCA would help to create a fair playing field for all economic actors (EO, SI). Soil & More Impacts explains a double advantage for commercial actors in the agri-food sector: with increasing legal requirements, TCA calculations will not continue to be an immense additional effort but will become less expensive and, at the same time, provide a clear competitive advantage in a world focusing increasingly on socio-ecological justice in economic undertakings. Truesday Coffee emphasizes the scientific data basis particularly, as sufficient availability of such enables a fair and less hierarchical relation between all players in the globally-spun agri-food networks. Latest developments in the German and European financial sector (e.g., the NFRD, parameters considered by rating agencies, etc.) complement TCA approaches (EO, SI). While Soil & More Impacts highlights its quality as a tool for risk minimization for businesses and companies, Eosta sees potential for a new, inclusive profit definition, in which social and ecological capital is inherent (SI). Nevertheless, it remains unclear whether a sufficient number of businesses can find the self-motivated courage to follow TCA standards to sustainably transform agri-food networks. Therefore, and as mirrored in the survey (cf. 3.4), governmental actors are perceived as responsible in guiding the implementation of TCA.

The importance of conclusive governance involvement in the implementation of TCA measures becomes especially apparent with regard to the possibility of TCA increasing the unjust distribution of wealth. On that account, social justice in its manifold expressions needs special addressing: while TCA methods strive for a fair distribution of wealth along global supply chains (e.g., in the form of living wages), it is also important to focus on persistent and rising distribution-related injustice within European (German) society (EO, SI, TD). To view and utilize TCA as a tool to analyze and adapt market distortions within the supply chains (pre consumer) is paramount (SI). Solely marketing eco-friendly diets or adding the previously externalized costs onto the final consumer price is considered insufficient as it counteracts the Polluter Pays Principle (SI). At the same time, certain consumer prices (for environmentally strenuous products) are likely to ascend (cf. Table 1), raising the issue of citizens' ability to pay for eventually higher food prices, especially for marginalized or underprivileged groups (TD). This ties in with several informal statements given in the consumer survey, where participants argued their income would not suffice for paying the true prices, especially for products that are already of higher cost levels. Questioned consumers also did state the price as the most important factor, when shopping for groceries (36.7%, $N=40$), implying a vulnerability towards rising prices at least in the examined sample.

Discussion

In our discussion, we will highlight points of interest that arise when critically assessing TCA methods, as well as discussing the responsibility for, and social justice issues arising with an implementation of TCA. The section closes with a summary of the potentials and challenges of TCA (cf. Table 3).

Methodological development

Through the medium of damage calculation and its subsequent monetization, and thereby achieved levels of transparency, TCA is helping agri-food players and the general public to make socio-ecologically just decisions (Gemmill-Herren et al. 2021). However, Eosta emphasizes that TCA is not a 'silver bullet' for a sustainable transformation in the agri-food sector. Amongst the experts and TCA actors, diverse views exist on the question whether a common TCA standard, as well as establishing a common TCA label, is a feasible and advisable step forward for the short-term future. A standardized approach in TCA is regarded as important prior to general implementation to make results comparable and increase the involvement of both practitioners and consumers (Baker et al. 2020; de Adelhart Toorop et al. 2021). Standardization also avoids shortcomings in the economic application, as varying TCA approaches (and resulting calculated costs) will likely lead the market to adopt 'the least expensive', less holistic or progressive approach (SI).

Table 3 Potentials and Challenges of TCA implementation

TCA: holistic tool considering multifaceted ecological services (and social impacts)

Potentials	Challenges
communication tool within the financial sector Conclusive monetization of ecological damages beyond emissions (planetary boundaries) Increased transparency regarding supply chains and cash flow	Variability in approaches: further improvement crucial before introducing TCA as a general intervention Primary data: may not be feasible for comprehensive implementation Secondary data: inaccuracy due to generalization in data acquisition
Compatible with existing frameworks Quantifies Polluter Pays Principle: integration of ecological and social costs into the definition of profit	Lacking pressure (formalization) to realize a socio-ecologically just accounting for the political, economic, and public sector
Risk minimization for businesses, profit maximization through front-running	initial Costs of TCA implementation
Communication and transparency tool for consumer knowledge Comparability of production processes	risk Of reputation loss and abuse due to different and non-transparent standards (greenwashing)
TCA label: Consistent global standard Trustworthiness	TCA label: No common standard yet Futility due to label weariness
instrument to tackle knowledge-action gap: Change in consumption behavior towards environmentally friendly diets (nudging) Reduction of animal products Increase in organic products	Increasing social injustice among consumers if implemented insensitive to economic inequalities and welfare regulations (ability to pay)

Unclear and differing calculation bases might yield distrust and subsequently less acceptance from consumers and could give way for improper application (i.e. greenwashing) (TD). When using TCA as a communication tool for consumers, the higher accuracy and accompanying complexity the more overwhelmed customers could be with the context. It is, however, pivotal to aim at an assessment, which is as precise as possible, for the use in conservative accounting practice, and to exactly monitor and compare differences in cultivation methods, which is needed to generate change in agricultural practice.

Another problem is seen with the wide range in the economic evaluation of damage: what is the price for clean air or water, a stable climate or biodiverse ecosystems? Not only is an evaluation likely to be subjective—as seen, for example, through the application of the WTP method where a sample is asked how much (e.g. an unchanged ecosystem) is worth to them personally (van Grinsven et al. 2013)—but can also be influenced, for example, through the environmental boundaries or goals that underlie the evaluation methods—for instance the increased price for CO2 equivalents from the UBA's Methodological Convention 2.0 (80€ per t) to 3.0 (180€ per t) (UBA 2012, 2019). Therefore, TCA calculations can be seen as steps in the right direction of integrating arising environmental or social costs into market prices. However, under current methodological advances it cannot represent the reality of the inherent economic damage. One practical resort to minimize such methodological shortcomings could be the conjoined implementation of price-based instruments (such as TCA) and absolute quantity measures (e.g. cap-and-trade schemes; such as presented in Weishaupt et al. 2020) that are aligned with existing declarations of commitment to curb climate change and the manifold ecological crises (e.g. the Paris Agreement) (cf. Rodi 2010).

Implementing TCA: administrative framework and citizens' acceptance

The governmental tardiness in comprehensive, effective action targeting the climate and global crises is amply known and scientifically discussed (IPCC 2019). The German government and European administrative bodies, like many around the world, have committed themselves to introduce the change necessary for economically viable and socially sustainable agriculture that provides (global) food security (German Federal Government 2021; Heinrich-Böll-Foundation 2019) and thus complies with the United Nations' Sustainable Development Goals (United Nations 2019).

Thus, the general need for TCA seems apparent with regard to current and upcoming policy standards and directives: by integrating ecological (and social) damages into economic measurements, TCA could be the logical instrument to execute novelties in European governmental initiatives (Bradshaw et al. 2021). Nevertheless, in the German Sustainability Strategy, it is written that the sustainable development of agri-food networks "can only succeed if politics, business and consumers assume their respective responsibilities" (German Federal Government 2021, p. 59). This could indicate that governmental structures do not necessarily see the responsibility to act lying primarily with them, thus underestimating their role as a driver of social innovation for transformation (Droste et al. 2016); and contrasts the consumers' opinion voiced in the survey, expressing the necessity of TCA implementation commenced through governmental bodies (cf. 3.4).

To elaborate on the role of general society (both in their consumer and citizen role), EO and SI postulate that the present difference between consumer and citizen needs to be bridged, so that consumption behavior complies with a common societal moral code and ethical foundations represented, i.e. in the Human Rights. This is in accordance with values represented in results from the consumer survey: the majority of participants agree that TCA is important and should be implemented (cf. 3.4), and awareness-raising measures such as the 'True Prices' campaign were seen as interesting (cf. 3.2). The customers' and experts' feedback to the 'True Prices' campaign thus reflects the general perceived strength of TCA as an important tool to create consumer awareness for occurring socio-ecological damages and increased cost transparency (Lord 2020; Gemmill-Herren et al. 2021; Hendriks et al. 2021). Holistic accounting approaches which combine ecological, social, and animal welfare factors were especially favored (cf. 3.4): this integrative potential of TCA can be highlighted as perceived core strength and should thus, especially in case of utilizing true price calculations for informational means, be incorporated if possible.

While raised levels of awareness can already be seen as beneficial in motivating individual sustainable consumption behavior (especially with regard to trendsetters and pioneers of change; EO), environmental psychology shows that more is needed to effectively achieve changes and translate knowledge into action (Kollmuss & Agyeman 2002; Stoll-Kleemann & Schmidt 2017). Utilizing TCA as a tool to broaden the public's knowledge on external costs can be seen as a valuable aid in reaching citizen's acceptance for incorporating new climate and biodiversity policy instruments. However, it is crucial to point out that neither informational campaigns like this nor individual behavioral change in general, suffice as means to overcome the present institutional lock-ins and to sustainably transform agri-food-networks.

Yet, an actual implementation of TCA could help to achieve this transformation, aligning with the underlying economic assumption and literature, which demonstrates that an in- or decrease in food prices has an impact on consumption behavior (Andreyeva et al. 2010). With regard to the tardiness of action in the industrial and administrative sectors, triggering behavioral change might seem promising, and thus nudging through price adaptations can be seen as a powerful strategy in which TCA can influence lifestyle and dietary behavior: by actually introducing 'true prices', the knowledge-action gap would be targeted (cf. Andreyeva et al. 2010; Michalke et al. 2021). To avoid shortcomings regarding distributional social justice (c.f. 4.3) while actively reducing market distortions and establishing sustainable agri-food networks, an intelligent incorporation of TCA into existing framework conditions is pivotal. This would ensue actually targeting a change in production practices themselves by consequently tying the costs of occuring damages to the polluting actor.

Suitable structures for the implementation of the price-based instrument of TCA within the spheres of taxonomy and lawmaking are adaptations of consumption taxes, CO_2-Pricing, the proposed renewal for the European non-financial Reporting Directive (NFRD; European Commission 2021), and state-level laws on supply chain transparency and due diligence (EO, SI, TD). Another beneficial outlook would be a combined execution of TCA and a reformed agricultural subsidy practice, focusing on good practice in agriculture and downstream processes (SI). In the European Union, in particular, subsidies have a very large impact on the current and future agricultural industry. However, a large portion is paid as generalized area payments (currently approx. 70%; European Commission 2021; Heinrich-Böll-Foundation 2019) and disregards special criteria of agricultural practice (such as organic produce or support in rural areas). Incorporating TCA could be the methodological centerpiece in a reformation of European subsidiary practice, creating veritable financial leverage towards encouraging meaningful, sustaining, and sustainable agriculture (SI).

Embedding social justice in TCA frameworks

Finally, the sensitive issue of social justice needs to be discussed in its multifaceted nature: nationwide aspects are, inequality amongst the different strata of consumers. Within the survey, many participants feared for their ability to pay for the 'true price', stating they could not afford it due to their low income (informal statements collected qualitatively). A socially just implementation of TCA is therefore crucial. If TCA was to be implemented with no differentiation on the receiving end of higher food prices, this would put even more pressure on already disadvantaged people with low incomes. On average, German households spend 10.8% of their monthly income on foodstuff (Bocksch 2020); participants of the survey, who reported lower net income, spend 16.17%. This difference could be explained by the case study's focus on a discounter customer base, representing lower-income strata than the German average (VuMA 2020). While an implementation of TCA is argued by research to be favorable regarding potentially reduced ecological costs (Gemmill-Herren et al. 2021; Bradshaw et al. 2021), it is important to address the issue of affordability. That true pricing will have a considerably greater effect on low-income strata is not just theoretically apparent, but also mirrored in customers' answers indicating that they would not have the economic means to choose freely between products.

Another important aspect for the general public's acceptance of TCA is that their moral values will not be taken advantage of for profit: it is paramount to emphasize once again that TCA must not be understood as a practice where solely the market prices for final consumers would rise; it is not conceptualized to merely lead to increasing consumer costs (SI). In its best manifestation, its methodological conception entails the Polluter Pays Principle and, where possible, the general avoidance of creating costs in the first place (Holden & Jones, 2021). As expressed by customers and interviewed TCA practitioners alike, suitable areas for application of TCA up to now are mostly focusing on its communicational capacities. TCA is a tool to inform businesses and consumers about current states of supply chains and areas of possible improvement of socially and ecologically unjust practices.

A practical application of TCA is present in several pockets of the market (e.g. fair trade or eco labels). So far, this can be classified as voluntary payments by downstream supply chains and is receiving sustained interest by customers, practitioners, and TCA scholars alike, as this practical engagement in TCA provides valuable insights and potentially competitive advantage. However, it is important to emphasize that only a factual implementation of TCA into the main strata of the markets would create sufficient leverage on producers to change their practices and eventually achieve a sustainable transformation. A number of potential pathways for carrying this out in a socially just way are being discussed (cf. 3.5), with the common impediment of lacking governmental interest or action. Regardless of the described barriers for implementation, according to the experts, TCA has the potential to actually contribute to human and planetary wellbeing by unskewing present market distortions borne from unassessed externalities.

The summary of relevant potentials and obstacles of TCA implementation is shown in tab. 3.

Conclusion

The general need for sustainable transformation is well-known and is a scientific consensus (as shown in the most recent IPCC report). Agri-food networks are one essential aspect, as agricultural practices and foodstuff consumption have a high impact on emissions, land-use change, and biodiversity. While a change in production practices themselves is presumably a valid effect of TCA (and arguably the main function), this case study puts the focus on the consumers' perspective. The general public's acceptance is deemed crucial for a successful and socially supported implementation of TCA.

Rising awareness about externalities is observable within society and informational campaigns like the one discussed are met with positive feedback and can help raise this awareness. However, the 'True Prices' campaign evaluation demonstrates a persistent knowledge gap regarding ecological damages in foodstuff production. Therefore, further educational initiatives targeted at consumers and citizens are urgently necessary. Nevertheless, the survey results of the informational campaign have shown that the overwhelming majority of consumers would reduce animal products and increase organic products in their food consumption if prices rose through the implementation of TCA.

Following the results of the consumer survey, we also see limitations to a possible sustainable transformation: to reach societal acceptance of TCA, a socially just implementation is paramount. An unreflected and fast introduction would pose monetary constraints for customers and thus discourage consumption change according to their knowledge and ecological or social values. Nevertheless, responsibility for TCA implementation, and at the same time the costs of paying for arising ecological or social damages, cannot solely lie with the consumer, as individual consumption behavior is not significant in comparison to institutional unsustainability. A sustainable, ecologically and socially just turn in agri-food networks is rated (very) important by consumers and experts alike, mirroring the scientific consensus on a needed change in agricultural practice and consumption habits. Therefore, legislators must be held accountable to design a market that incentivizes holistically sustainable consumption, as well as production, without disregarding feasibility for the individual. Comprehensive compulsory adaptations by legislative powers are identified as necessary and socially anticipated, as long as they are formed in a transparent and just manner. Therefore, the biggest pitfall in implementing TCA would be an increase in consumer costs without generating change along the lines of production and economic value chains. This is in line with the expert feedback, which highlights the need for a sensible integration of TCA into legal and administrative frameworks.

TCA methods are also yet to be incorporated into conventional business' accounting as a transparency tool and competitive advantage that all businesses can or should access. Presently, a growing number of initiatives and networks working on and with TCA exist. To optimize consumers' confidence, TCA research has to work towards standardized calculation methods and develop useful tools ready for implementation. Those should facilitate a sensible level of preciseness without compromising on understandability and transparency. An implementation within existing agri-food networks necessitates transdisciplinary exchange and guidance between the economic sector, governments, and consumers.

TCA is in line with the mega-trend of sustainability. It encourages modern economic principles like the 'Economy for the common good' or the 'Doughnut Economy' and presents as one tool of many necessary to counteract the multi-dimensional crises that global society faces today. Valuable lessons can be learned from the experience gained within the existing TCA structures. Going further, i. a. a combination of different, mutually inclusive, economic and regulatory instruments seems promising. Research, inter-, and transdisciplinary work should be further extended to enable fulfilling the SDGs and national sustainability strategies.

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