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RESEARCH ARTICLE

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Biodiversity impact of food waste

Quantification for supply chain stages and products in Germany

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Abstract

Reducing food waste could lower pressures on land resources and thereby contribute to the mitigation of global biodiversity loss. The reduction of food waste and biodiversity loss are also specified in the Sustainable Development Goals 12.3 and 15 of the United Nations. However, which supply chain stages and food products to target with policy measures is hardly known. Especially, a differentiation of the impact after sub-stages and taxa is still missing and is therefore quantified in the present study. The food waste mass at five supply chain stages and seven sub-stages in Germany was calculated and differentiated after 204 food products. All products were traced back to their countries of origin, in which their land use impact on mammals, birds, amphibians, reptiles, and plants was quantified. A new approach was developed to calculate the detailed feed demand for animal products. Germany's avoidable food waste (food that was edible before its disposal) leads to 0.3 vertebrate and 1.5 plant species being potentially lost globally. Household-level waste is responsible for 47% of this species loss, while food services show the largest impact per mass, with individual catering being as influential as one-person households. The most influential products are obtained from pigs and cattle. Among vertebrate taxa, mainly amphibians are affected, occurring in the mainly affected country Brazil. The results can be used to formulate policies that target, for example, individual catering or display the impact of animal products and their feed demand.

KEYWORDS
animal products, environmental impact, food waste, industrial ecology, species loss, value chain

1 | INTRODUCTION

Anthropogenic impacts are leading to such a rapid biodiversity loss that it might irreversibly affect processes and resiliencies of global ecosystems (Steffen et al., 2015). Two-thirds of this biodiversity loss is caused by land use mainly associated with the production of food (Wilting et al., 2017). One-third of this production does not reach human consumption but ends as food waste (synonymously with food loss in this study) (Gustavsson et al., 2011). The recovery of biodiversity and ecosystems is the aim of global and European-level policies, notably the European Union's Biodiversity Strategy 2030, which states that the underlying drivers of biodiversity loss should be addressed (EU, 2020). Food waste, as one of those drivers, is addressed in the sustainable development goals (SDG) of the United Nations (UN), aiming to reduce food waste at all supply chain stages until the year 2030 (UN, 2015). Preventing food waste is not only important for the recovery of biodiversity, but also for ecosystem services, food security, and the reduction of resource use and thus economic costs (Bajželj et al., 2020).

The amount of food waste has been quantified for different supply chain stages (agricultural production, processing, distribution, food service, households) and food products in previous studies ranging from global to national scales. The environmental impacts of food waste have mainly been derived for greenhouse gas emissions and land use demand. Previous studies on this topic are listed in Table S1 of Supporting Information (SI) S1. In contrast, the impact of food waste on biodiversity at different supply chain stages has only been quantified once in the literature so far: Beretta et al. (2017) analyzed the impact of avoidable food waste (AFW, food that was edible before its disposal) based on the food consumption in Switzerland in 2012 and described the stage households and the products cocoa, beef, and wheat as most influential.

However, a differentiation of the impact between taxa and the inclusion of sub-stages in the supply chain is still missing in the literature, although it would help to formulate more targeted policies. Therefore, this study is the first to identify which sub-stages have the largest biodiversity impact via their food waste. Calculations are conducted on a high level of detail with 204 food products and as a novelty differentiating the impact after four vertebrate taxa and plants. To reach this level of detail, a new approach concerning animal products was developed which allows for calculating the demand for single feed products to produce meat, milk, eggs, etc. The impact is quantified by using the land demand the products have in their countries of origin. Other environmental pressures affect biodiversity loss as well, especially climate change (Sanyé-Mengual et al., 2023). However, climatic impacts appear on a longer time scale and no factors exist to differentiate them between different taxa so far. As the differentiation between taxa is one of this study's aims, the focus lies on land use, which is also described as the most prominent pressure on biodiversity in studies on food consumption (Crenna et al., 2019; Wilting et al., 2017). As a reference, Germany was chosen, as for this country a profound data basis exists to quantify the mass and composition of food waste along the supply chain, and it can be used as a template for other industrialized countries. Herein developed results can be used for the future prioritization of measures against food waste, while the approach of transferring animal products into single feed products can be used as orientation for other analyses.

2 | METHODS

2.1 | Scope and definitions

2.1.1 | System boundaries

The calculations were conducted for Germany in 2015, as by far most information on food waste mass and composition exists for this year. A territorial approach was applied, which means a complete inclusion of food waste from German production and processing, even if the products are exported and consumed in another country. In return, food waste from production and processing in other countries is excluded, even if the corresponding products are imported to Germany (Caldeira et al., 2019) (Figure 1). This approach is especially suitable for political measures targeting food waste within the country.

2.1.2 | Food waste definition

In this study, food waste is defined as products intended for human consumption (including beverages while excluding alcohol) that were removed from the food supply chain to be disposed of or utilized for non-food use (Beretta et al., 2017). In the literature, the term food loss also exists for products that exit the supply chain before reaching the retail sector (UNEP, 2021). As this term is often not differentiated from food waste and describes products with the same material characteristics, both terms are used synonymously in this study. Food waste is further classified as AFW and unavoidable food waste both adding up to total food waste. AFW comprises products that were edible before their disposal, while unavoidable food waste describes products that were inedible (e.g., bones) or not avoidable with available technologies or reasonable efforts. This study focuses on AFW, as it entails a reduction potential. These definitions are consistent with Beretta et al. (2017).

2.1.3 | Food supply chain

The impact of AFW in Germany was quantified for the whole food supply chain, distinguished into five stages: agricultural production, processing, distribution, food services, and households. Following the European directive 2018/851 (EU, 2018), the agricultural production stage begins with postharvest waste, while food remaining on the field is excluded from the definition of food waste. Distribution is further divided into the sub-stages wholesale and retail (Schmidt et al., 2019). Food services are divided into communal catering (e.g., canteens) and individual catering

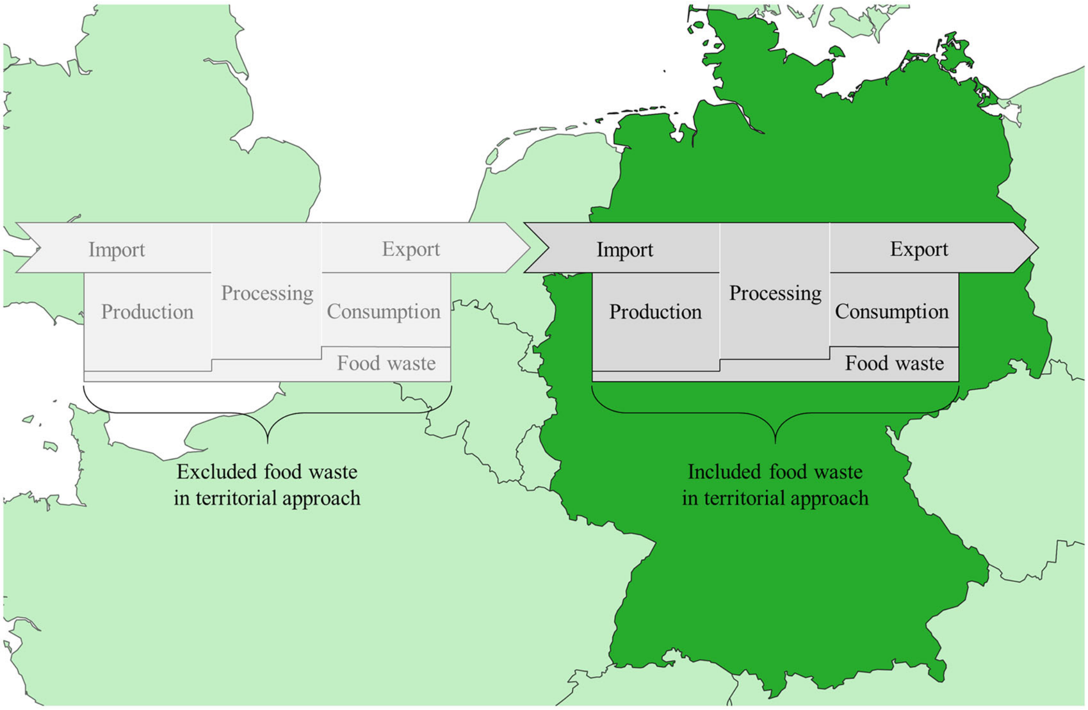

FIGURE 1 System boundaries of the territorial approach. The food waste occurring in the area of Germany is included in the calculations. The stages of distribution, food services, and households belong to the "consumption" part.

(e.g., restaurants) (Göbel et al., 2014). Households are divided according to their size into one-, two-, and three-plus-person households (Hübsch & Adlwarth, 2017), to identify which households have the largest impact per size and person.

2.1.4 | Food products and categories

The products found in the food waste are defined consistently with the items from the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2015i). They comprise 100 primary products (e.g., wheat) and 104 processed products (e.g., bread). These products were assigned to seven categories, combining the ones defined by Schmidt et al. (2019), Göbel et al. (2014), Lebersorger and Schneider (2014a), Hrad et al. (2016), and Hübsch and Adlwarth (2017): cereals, fruits, vegetables (including potatoes and mushrooms), plant oils (including nuts and oleiferous fruits), dairy and eggs, meat (including offal and animal fats) and sugar, stimulants, and spices (including cocoa and coffee). The products and categories are listed in Table S2 of SI S1. Fish and honey were excluded as they affect biodiversity by other environmental pressures than their land demands (Scherer & Pfister, 2016).

2.2 | Mass of food waste

To calculate the mass of each product in the AFW along the supply chain, the mass of the whole AFW was first differentiated after food categories. The mass of AFW for the five supply chain stages and the sub-stages of distribution and food services in 2015 was taken from Schmidt et al. (2019). The mass and composition of household waste were differentiated for three different household sizes with data obtained by Hübsch and Adlwarth (2017), which the authors received from the German Federal Ministry of Food and Agriculture. The AFW mass of each stage and sub-stage was differentiated into food category composition according to the literature sources listed in Table 1 and illustrated in Figure S1 of SI S1. The products are listed in Tables S3 to S8 and details on calculating waste shares are in Sections S2.2 and S2.3 of SI S1.

To further differentiate the food categories on the product level, data from the FAO on the produced, processed, and consumed product quantities in Germany in 2015 were utilized (FAO, 2015e, 2015f, 2015g, 2015h). It was assumed that in each food category, the same mix of products was wasted as it was produced (stage agricultural production), processed (stage processing), or consumed (stages distribution, food services, and households) because of the comparable properties of products (e.g., perishability) (Beretta et al., 2013). This way, categories like fruits were further differentiated into apples, bananas, etc. The handling of unspecified and highly processed products is explained in Section S2.4 of SI S1.

TABLE 1 Literature sources to differentiate the mass of avoidable food waste at each supply chain stage into food categories.

Stage and sub-stage	Agricultural production	Processing	Distribution: Wholesale	Distribution: Retail	Food services: Communal catering	Food services: Individual catering	Households: 1, 2, and 3+ persons
Source	Schmidt et al. (2019)	Schmidt et al. (2019)	Göbel et al. (2014)	Lebersorger and Schneider (2014a, 2014b)	Hrad et al. (2016)	Hrad et al. (2016)	Hübsch and Adlwarth (2017)
Country	Germany	Germany	Germany	Austria	Austria	Austria	Germany
Year	2015–2016	2015	2012	2012	2014–2015	2014–2015	2016–2017
Sample size	Not mentioned	100	3	700	23	26	6000

Beverages were differentiated on the product level using the consumed quantities listed in the statistical yearbook on nutrition, agriculture, and forestry (BMEL, 2017), as further described in Section S2.5 of SI S1. The data for the food service stage do not contain beverages in the AFW (Hrad et al., 2016). The derived AFW at each stage at the product level is listed in Table S20 of SI S2. The products were then summarized into the seven categories of this study to illustrate the results. As a reference point, the biodiversity impact of German food consumption in 2015 was calculated as well, using the masses of consumed food in the supply utilization accounts from the FAO (2015e, 2015f, 2015 g, 2015h) and beverages from the statistical yearbook on nutrition, agriculture, and forestry (BMEL, 2017). Details on calculating the consumption impact are in Section S2.6 of SI S1.

2.3 | Country of origin

The yield and the biodiversity impact of a product depend on the country in which its primary product was cultivated (Chaudhary & Kastner, 2016). Therefore, all products in the AFW were traced back to their countries of origin. Regarding the stages of processing, distribution, food services, and households, the same mix of countries was assumed for each product in the food waste, as for the similar product in the consumed food (Beretta et al., 2017). Bilateral trade data usually show imports only from the country where the product's last processing took place. Therefore, the method from Kastner et al. (2011) was utilized to trace the products back to their countries of origin. This method builds on the assumption that the consumption in a country consists of proportional shares of its domestic production and its imports. The same applies to exports and can be used to find the share of products being re-exported and to trace them back to their countries of origin (Kastner et al., 2011). Data on the production and bilateral trade for 197 countries were obtained from the FAO (2015a, 2015b, 2015c, 2015d, 2015i).

In the first step, the 104 processed products in the bilateral trade data were converted into their primary equivalent, making a combination with the production data possible. As proposed by Kastner et al. (2011), caloric contents were used for this conversion: For example, for 1 kg of bread (263 calories/100 g), 0.8 kg of wheat is needed because of its higher caloric content (330 calories/100 g) (Watt & Merrill, 1975). The caloric contents were obtained from the FoodData Central by the US Department of Agriculture (USDA, 2020), Watt and Merrill (1975), and Feedipedia (INRA et al., 2020) (Table S9 of SI S1). The conversion of processed sugar in sugar beet and sugar cane made an aggregation of those two primary products necessary, as explained in Section S2.7 of SI S1. Then, all plant products were traced back to their countries of origin, while for animal products, intermediate steps were introduced as explained in Section 2.4. For the stage of agricultural production, all plant products originate from Germany, where the crop fields are located.

2.4 | Transferring animal products into feed demand

Like plant products, animal products were also converted into primary equivalents and traced back to their countries of origin. As animal products affect land use by the required feed, additional conversion steps were introduced. The feed requirements (in dry mass) per kg of the carcass (for beef cattle, sheep and goats, broiler chickens [also used for turkey], and pigs), kg of milk (for dairy cattle), and kg of eggs (for layer chickens) were obtained from Mekonnen and Hoekstra (2012). In the next step, this dry mass of feed was differentiated into six feed categories of roughages and six feed categories of concentrates for beef cattle, dairy cattle, and sheep and goats, according to Opio et al. (2012). For broiler chickens, layer chickens, and pigs, the dry mass of feed was differentiated into between 12 and 16 feed categories of concentrate feed, according to MacLeod et al. (2012). All three sources listed values for different world regions that were aligned to 11 world regions used in the present study. The attribution of countries to the world regions is shown in Table S10 of SI S1. The dry mass values were converted into fresh mass, using the water content of each category according to USDA (2020), Watt and Merrill (1975), and Feedipedia (INRA et al., 2020). Water contents are listed in Tables S11 and S12 of SI S1. The feed categories were further differentiated on a product level using data on feed in 197 countries in 2015 listed by the FAO (2015e, 2015f, 2015 g, 2015h) (Tables S13 and S14 of SI S1). The exclusion of unlisted feed products is explained in Section S2.8 of SI S1. The roughage fresh grass (from the grazing of ruminants), hay, silage, and crop residues were assumed to have the same country of origin as the animal products (Scherer & Pfister, 2016). All other feed products originate from domestic production as well as from imports of plant products (MacLeod et al., 2012). Therefore, they were further traced back, again using the method from Kastner et al. (2011), now starting from the countries in which the animal products were produced.

2.5 | Impact on biodiversity

Knowing the countries of origin, the required land use area and the biodiversity impact in those countries were calculated. All plant products and concentrate feed products were converted into cropland areas using yield values for each country of origin in 2015 as listed by the FAO (2015a). As no yield values for grass were available, they were calculated based on the aboveground net primary productivity in the mass of carbon per area and year in 11 world regions obtained from Fetzel et al. (2017). A carbon content factor of 50% was used to convert the mass of carbon into dry matter biomass, as proposed by Fetzel et al. (2017). This source was chosen as it differentiates the yield values after 11 world regions, fitting the spatial resolution of the sources used for the feed demand under 2.4. The calculated yield values were compared with the literature and are in the same range as the values from, for example, Deak et al. (2007). The conversion of hay, silage, and crop residues is explained in Section S2.9 of SI S1. The grass yields are listed in Table S15 of SI S1. These grass yields were used to calculate the pasture area embodied in animal products.

To derive the impact on biodiversity from the land use area, the global occupation characterization factors of Chaudhary and Brooks (2018) were utilized. This source was chosen as the factors are differentiated after the land use types—cropland and pasture—and allow for the calculation of food waste impact on the four vertebrate taxa—mammals, birds, amphibians, and reptiles—as well as on plants. They are based on a countryside species–area relationship model, relating the naturally possible number of species in an ecoregion to the number occurring with human land use. Via the affinity the taxa have to different land use types and the share the land use types have within each ecoregion, the "regional potential species loss per square meter" in each ecoregion is derived. By multiplying this value with a vulnerability score containing the endemism and IUCN Red List status of each taxon, Chaudhary and Brooks (2018) finally brought the characterization factors on a global level in the unit "global potential species loss per square meter." These factors can optionally be aggregated by dividing them by the total number of species within each taxonomic group and summing the values up across all five taxa (Chaudhary et al., 2015). The resulting factors in the unit "global potentially disappeared fraction per square meter" were used by Beretta et al. (2017). They do not allow for differentiation between the five taxa but were calculated in addition to comparing them to the results of this study. The factors differ for the 197 countries of origin and the two land use types used in this study. As Chaudhary and Brooks (2018) further differentiate the characterization factors for three land use intensities, the globally most common intensities in terms of their area were used: intense use for cropland and light use for pastures. An uncertainty analysis was conducted to illustrate the effect of the land use intensities.

3 | RESULTS AND DISCUSSION

In 2015, 81.1 million tonnes of food were consumed in Germany (eaten or wasted at distribution and the subsequent stages), while 6.0 million tonnes ended as AFW in the whole supply chain (both values excluding fish and honey). If the amount and composition of the consumed food in Germany stay at the level of 2015, it potentially causes the global loss of 4.2 vertebrate and 26.1 plant species. The impact of AFW in Germany reaches 0.3 vertebrate species being potentially lost globally, comprising 28.2% mammals, 30.3% birds, 34.3% amphibians, and 7.2% reptiles, as well as the loss of 1.5 plant species. Chaudhary and Brooks (2019) calculated 5.0 mammal, bird, and amphibian species being potentially lost globally because of the domestic and imported land use of Germany.

3.1 | Impact per stage and sub-stage with corresponding food categories

The impact on biodiversity is mainly caused by households (responsible for 46.9% of the AFW impact on vertebrate and plant species), followed by food services (27.2%), agricultural production (10.9%), distribution (8.2%), and processing (6.9%) (Figure 2). The impact per mass increases along the supply chain. Agricultural production has a small impact per mass, processing the smallest among all stages (accounting for 1.0 million tonnes or 16.3% of the overall AFW). Food services show the largest impact per mass, compared to processing with a four times as high impact on biodiversity. This impact is almost equally caused by the sub-stages of communal and individual catering, yet individual catering shows a larger impact per mass. Also, for the household sizes of one, two, and three-plus persons, the mass and composition of AFW are almost similar between the sizes, leading to almost similar impacts on biodiversity (30.9%, 29.3%, and 39.8% of households' impact), but converting the value to an impact per capita shows that people in a one-person household affect biodiversity almost twice as high as people from a two- or three-plus-person household (15.4×10^{-9}

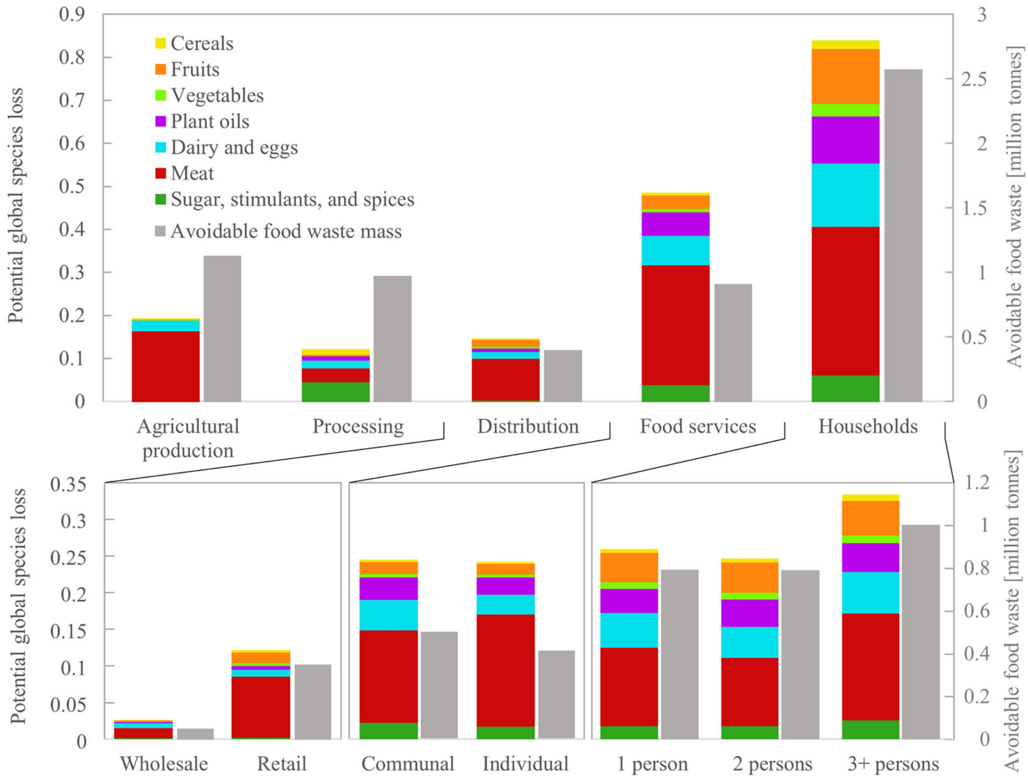

FIGURE 2 Potential global species loss of vertebrate and plant species caused by the avoidable food waste (AFW) of the stages and sub-stages. In one-person households, this impact is caused by 16.9 million people, in two-person households by 28.0 million people, and in three-plus-person households by 36.2 million people. The colors indicate how much the food categories contribute to this impact. The gray bars show the mass of AFW. Underlying data for this figure are available in Tables S16 and S17 of Supporting Information S1 and Table S19 of Supporting Information S2.

species potentially lost globally per person compared to 8.8×10^{-9} and 9.2×10^{-9}). The impact of distribution is mostly coming from retailers (82.3% of this stage's impact), less from wholesalers (17.7%). The calculated biodiversity impact is mainly caused by meat in the stages of agricultural production (84.4% of the impact from this stage), distribution (66.0%), food services (57.3%), and households (41.3%). Only in processing, the impact is dominated by sugar, stimulants, and spices (37.4%). The detailed values are in Tables S16 and S17 of SI S1. The impact differentiated between vertebrate and plant species is illustrated in Figures S2 and S3 of SI S1.

Regarding Switzerland, Beretta et al. (2017) found that the largest impact on biodiversity is also caused by households. As reasons for the larger per capita AFW mass of one-person households, Jörissen et al. (2015) discuss that recipes are usually written for more people and that food is often only purchasable or cheaper in larger packaging sizes. The second reason was also especially mentioned by one-person households in the study that serves as a basis for the present analysis (Herzberg et al., 2020). With 27.2%, the proportional impact from food services in this study is three times as high as observed by Beretta et al. (2017). However, the share of the AFW mass is four times as high as in Switzerland, which implies a comparable impact per mass. The large impact per AFW mass of food services and especially of individual catering in the present study mainly occurs because of the large share of wasted meat. This is probably caused by the larger shares of meat left on the plates (Hrad et al., 2016). Voca et al. (2020) also reported for Croatia that 12.1% of the AFW on plates in restaurants is meat. The inclusion of beverages in the AFW of food services might decrease the impact per mass compared to other stages. Still, for example, households have a share of only 8.0% of beverages in their AFW, consisting mainly of coffee with a high impact per tonne. Kummu et al. (2012) calculated the cropland needed for the food that ends up as AFW along the food supply chain. They also calculated food remaining on the field as AFW, which is excluded from the comparison as it does not appear in the present study's definition. Kummu et al. (2012) received for Europe a comparable value of 8.3% regarding the processing stage. For distribution, Kummu et al. (2012) reported a share of 11.2% from the AFW impact, which is larger than the 8.2% found in the present study. The proportional impact of distribution is larger than the share this stage contributes to the AFW mass. The main reason is the large share of wasted meat (13.9%) at this stage and its sub-stages. Meat especially occurs in the AFW of the retail sub-stage because of its short shelf-life, which is chosen to prevent bacterial growth and associated health issues (Buisman et al., 2019). Agricultural production also has a large share of meat (13.2%) in its AFW mass. Nevertheless, the impact per mass is only half as large as for distribution. Here, the main reason is that the plant products in this stage originate from Germany, where they have a smaller impact on biodiversity per tonne.

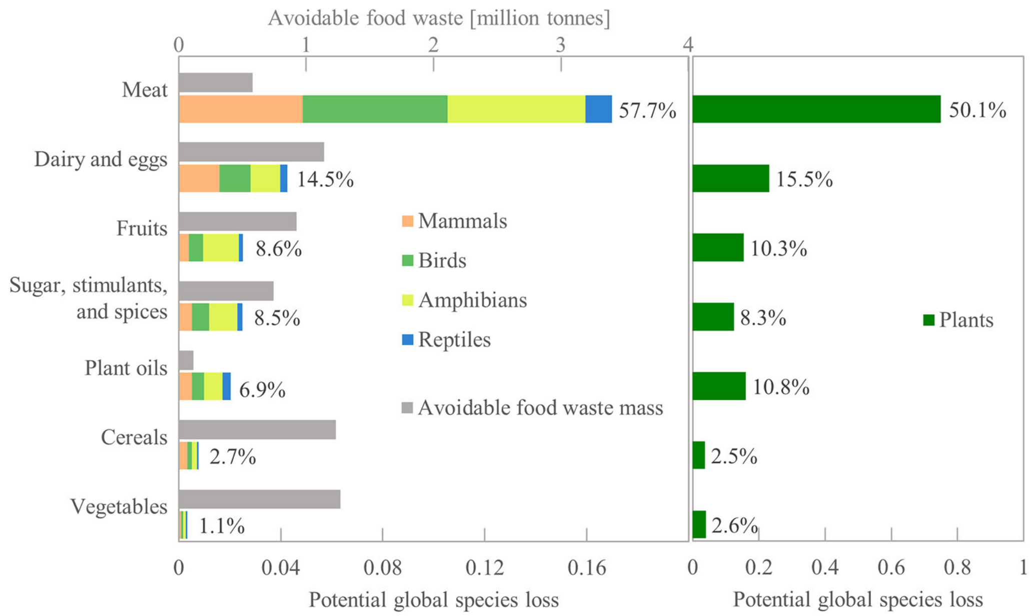

FIGURE 3 Potential global species loss caused by avoidable food waste (AFW) in different categories, with the percentage this impact has among all categories. The impact is differentiated for four taxa and plants; the gray bars show the mass of AFW. Underlying data for this figure are available in Table S18 of Supporting Information S1.

The SDG of the UN aims to reduce both food waste and biodiversity loss in SDGs 12.3 and 15 (UN, 2015). Concerning both goals, the already implemented focus on retail and consumer levels is useful, as the results of this study indicate that those stages have the largest impact per mass. Policies can be formulated to target especially one-person households, as their impact on biodiversity per person is almost twice as high as in other household sizes. Policies giving retailers incentives to sell food in smaller quantities or packaging sizes could prevent AFW in small households. Additionally, the same impact on biodiversity as from one-person households is also reached by individual catering while accounting for only around half as much AFW mass. Therefore, for example, incentives to donate leftover food from buffets in hotels and restaurants could have an amplified effect on reducing the impact on biodiversity and reaching SDGs 12.3 and 15.

Rebound effects might offset around two-thirds of the avoided food waste and the associated benefits on biodiversity, as the higher efficiency lowers the price and increases the demand for food and food security. Yet, these rebound effects were calculated under a costless AFW reduction scenario and could be nullified when the price for AFW reaches one-third to one-half of the food price (Hegwood et al., 2023).

3.2 | Impact per food category on taxa and impact of single products

Summarized for the food categories from all stages, the impact on biodiversity is mainly caused by meat (responsible for 57.7% of the AFW impact on vertebrate species, 50.1% on plant species) while accounting only for 9.7% of the AFW mass (Figure 3). The impact of dairy and eggs is already considerably lower (14.5% on vertebrate species, 15.5% on plants). The smallest impact is caused by vegetables (1.1% on vertebrate species, 2.6% on plant species) and cereals (2.7% on vertebrate species, 2.5% on plant species) while accounting for the most mass in AFW (21.1% and 20.5%, respectively). Within each category, the largest impact on mammals occurs for cereals (42.0% of this food category's impact) and dairy and eggs (37.5%). The largest impact on amphibians occurs for fruits (55.3%) and sugar, stimulants, and spices (44.4%). Vegetables primarily have an impact on amphibians (32.5%) and mammals (30.6%). Birds are slightly less affected, with up to 33.5% of the impact from meat. Reptiles are the least affected taxon in each category, with up to 16.4% of the impact from vegetables. The impact and mass from food categories are listed in Table S18 of SI S1.

All products based on the same primary product were aggregated, showing that the impact on vertebrate species is mainly caused by pork (responsible for 17.5% of the AFW impact on vertebrate species), followed by lard (15.8%). (Products with the largest impact in Figure 4.) After these two products obtained from pigs, two products from cattle account for a large share of the impact on vertebrate species, namely dairy (12.7%) and beef (12.6%). The impact on plant species shows a comparable pattern. The AFW impact and mass of all products can be found in Table S19 of SI S2. Beretta et al. (2017) also found a high impact from beef (11.0%), which is lower than in the present study, mainly because the share of beef in the AFW mass is lower for Switzerland (around 0.7% compared to 1.3% in Germany). For the food consumption in whole Europe in 2015, Crenna

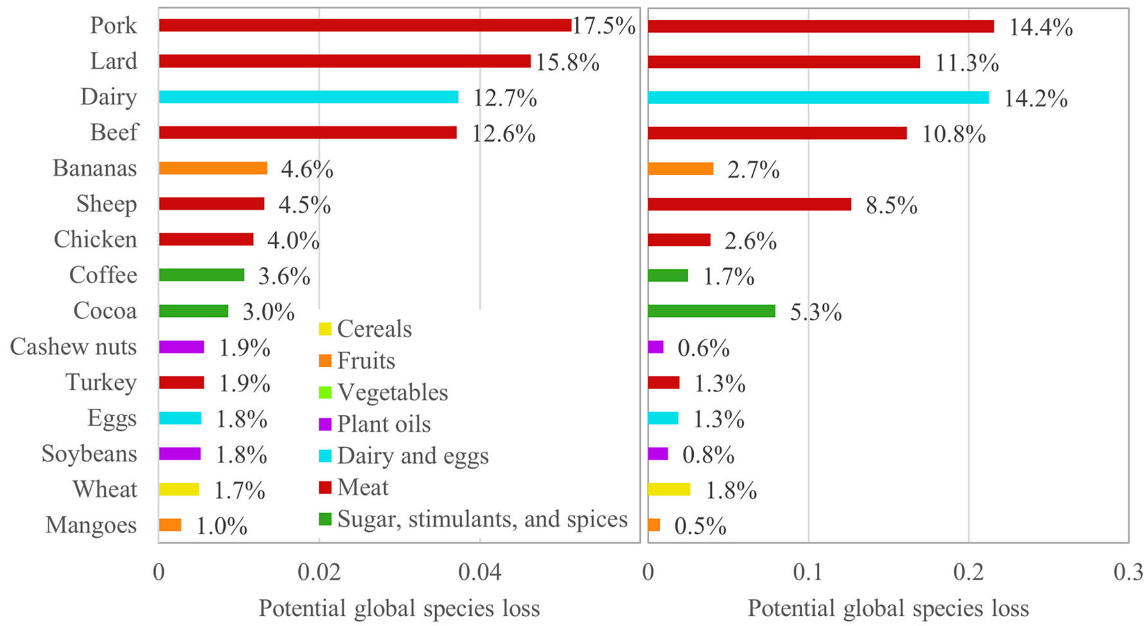

FIGURE 4 Potential global species loss of products aggregated after their primary products. The 15 aggregated products with the largest impact in avoidable food waste are shown, with the percentage values they have from this impact. The colors illustrate which food categories the products belong to. The left part of the diagram shows the impact on vertebrate species, while the right part shows the impact on plant species. Underlying data for this figure are available in Table S20 of Supporting Information S2.

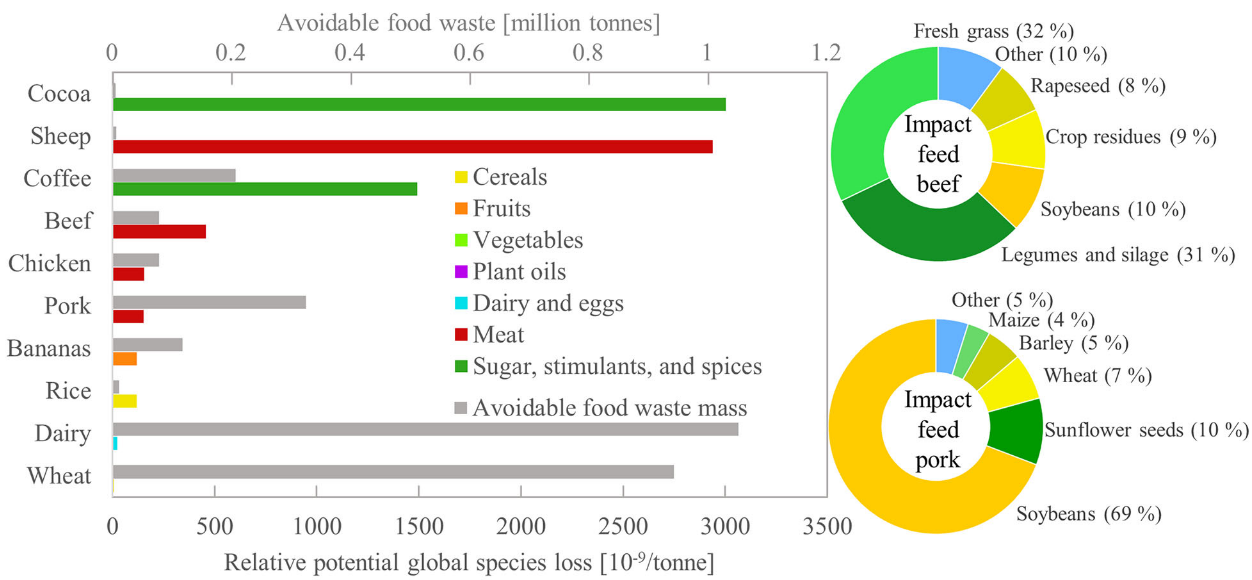

FIGURE 5 Impact on vertebrate species per tonne of products consumed in Germany and avoidable food waste mass of products with the same primary product. The diagrams on the right illustrate how the impact of the animal products beef and pork is composed of their feed. Underlying data for this figure are available in Tables S21, S24, and S25 of Supporting Information S2.

et al. (2019) estimated pork and beef to have the largest impact on biodiversity as well, together accounting for around 44% of the potential global species loss.

The following impacts per mass (relative impacts in the unit species/tonne) are listed for the primary products and on vertebrate species. By far, the largest impact per mass results from vanilla (80,700 × 10^{-9} species potentially lost globally per tonne). Cocoa has an impact of 3004 × 10^{-9} species/tonne, and coffee of 1490 × 10^{-9} species/tonne (Figure 5). The impact of meat from sheep consumed in Germany is 10 times higher (2938 × 10^{-9} species/tonne) than of meat from sheep produced in Germany (225 × 10^{-9} species/tonne), as the mix of countries for the feed is different. Beef has an impact of 455 × 10^{-9} species/tonne as it is consumed in Germany and 282 × 10^{-9} species/tonne as it is produced in Germany, mainly

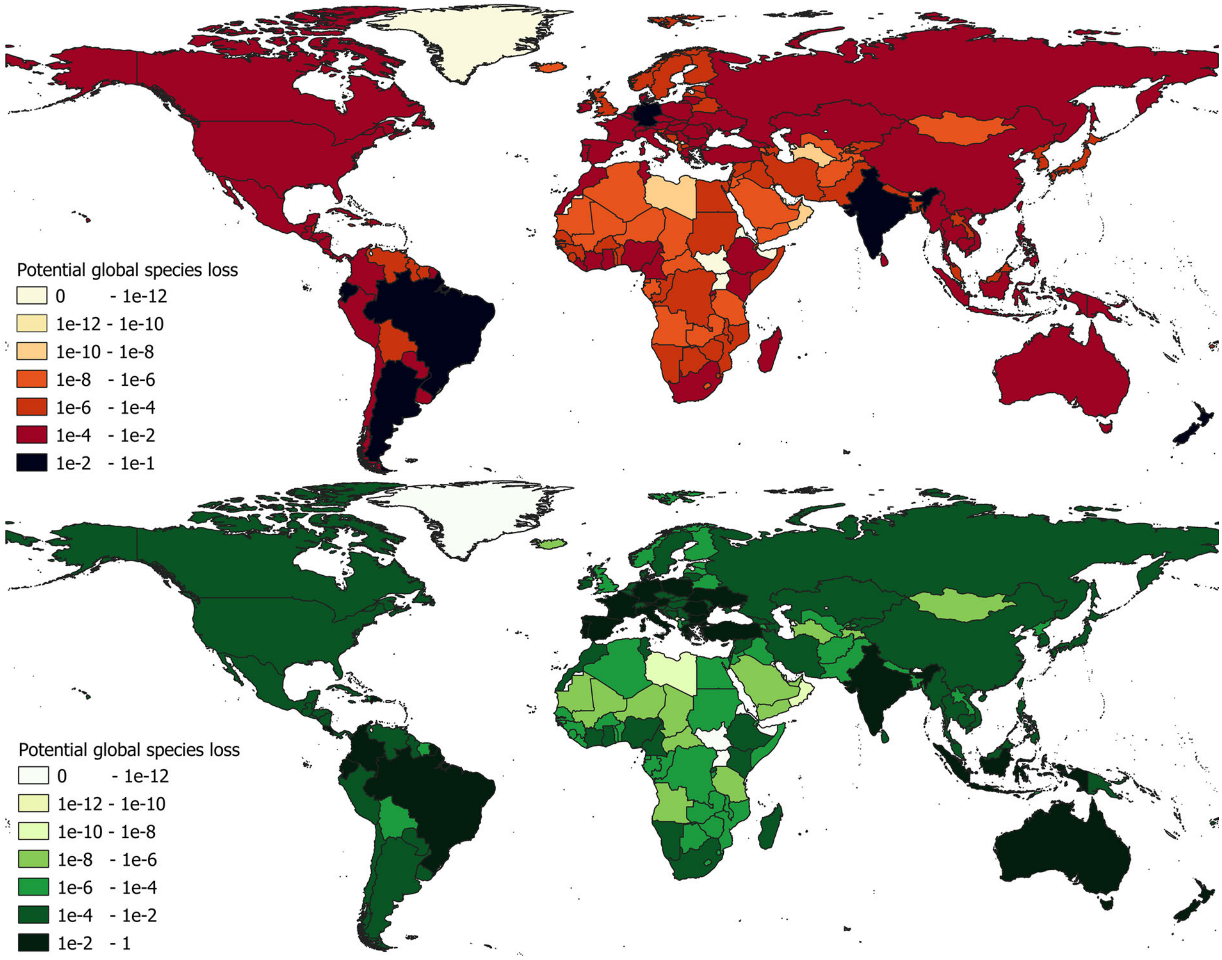

FIGURE 6 Potential global species loss in the respective countries, caused by the avoidable food waste in Germany in 2015. The upper map shows the impact on vertebrate species and the lower map the impact on plant species. Underlying data for this figure are available in Tables S22 and S23 of Supporting Information S2.

because of its large feed demands. Wood et al. (2019) examined dietary shifts in the United States and also identified beef as one of the products with the largest land requirements per tonne. 47.0 tonnes of dry mass feed per tonne of cattle carcass are needed, averaged over all world regions and production systems (for comparison, the factor is 5.8 in the case of pig carcass) (Mekonnen & Hoekstra, 2012). Therefore, pork has a smaller relative impact of 149×10^{-9} species/tonne as it is consumed in Germany and 138×10^{-9} species/tonne as it is produced in Germany. Yet, it has a larger share of 5.4% in the AFW. The impact per tonne of primary and processed products, differentiated after four vertebrate taxa and plants, is shown in Table S21 of SI S2. The impact of ruminants is dominated by the fresh grass as well as the legumes and silage in their feed. For beef consumed in Germany, they account for 32.1% and 30.8% of the impact, while soybeans, crop residues, and rapeseed are less important (Figure 5). For pigs and poultry, soybeans are by far the most influential feed, accounting for 69.2% of the impact from consumed pork. The impact of single feed products in their countries of origin is listed in Tables S24 and S25 of SI S2.

A policy option to reduce the biodiversity impact of AFW on a product level could be the development and introduction of a biodiversity label. Displaying the large impact per tonne of, for example, cocoa, sheep, and coffee could inform not only about the impact of AFW but of consumption in general. This would address the influential household stage already during the food is purchased to possibly alter consumption patterns to help reach SDG 15 on preventing biodiversity loss.

3.3 | Impact in countries of origin

Distributing the AFW impact of Germany to the countries in which plant products or the feed for animal products were cultivated shows that the impact on vertebrate species occurs with 23.9% mainly in Brazil, followed by 18.0% in Germany (Figure 6). The impact on vertebrate species is between 5.4% and 3.5% smaller for India, New Zealand, Argentina, and Ecuador. The impact on plant species occurs with 15.2% mainly in Spain, followed by Brazil with 11.4%, and New Zealand, Italy, France, and Germany with between 9.0% and 8.1%. The AFW impact in Brazil mainly occurs because of pork and lard (responsible for around 30.0% of this country's impact, respectively, on vertebrate species and plant species). In Germany, the impact on vertebrate species is dominated by dairy and beef; the impact on plant species in Spain mainly occurs because of almonds, pork, and olives. The impact on vertebrate as well as plant species in New Zealand is around 90.0% dominated by sheep. The impact per country and product is listed in Tables S22 and S23 of SI S2. Bananas, coffee, and cocoa, as the non-animal products with the highest share of the AFW impact in Germany, all originate from sub-tropical and tropical countries. There, their cultivation mainly affects amphibians. The cultivation of the other products ending as AFW affects mammals and birds.

For the impact on vertebrate species occurring outside the target country, Beretta et al. (2017) calculated for Switzerland 79%, similar to the 82% in this study. Yet, the impact on plants occurring outside of Germany is 92% even higher, showing the importance of differentiating after the affected taxa. The large impact sheep have in New Zealand occurs as this countryt's landscape is dominated by grassland for sheep and beef that comparably recently transformed the former forests (Pannell et al., 2021). An explanation for the larger impact of bananas, coffee, and cocoa on amphibians is probably their higher diversity in tropical countries. This taxon has a strong latitudinal biodiversity gradient, meaning its species richness is highest in tropical regions and declines considerably toward the poles (Pyron & Wiens, 2013).

3.4 | Limitations and research outlook

From the literature sources used to differentiate the mass of AFW after different food categories (Göbel et al., 2014; Hrad et al., 2016; Hübsch & Adlwarth, 2017; Lebersorger & Schneider, 2014a; Schmidt et al., 2019), the low sample size of 3 for wholesalers and of 23–26 for food services brings uncertainty to these sub-stages. The temporal coverage of these sources is close to 2015, ranging from 2012 to 2017. Geographically, most sources are from Germany. Values taken from Austrian studies might need to be rechecked when values from Germany are available.

The uncertainty analysis shows the effect of replacing the characterization factors for cropland and pastures by the highest and lowest of the three intensity levels (intense use and minimum use). For vertebrate taxa, this results in a range of 0.30 to 0.28 species being potentially lost globally. For plants, this range is larger with boundaries of 1.56 and 1.17, which indicates a higher dependency of plants on different intensity levels. This range will decrease when yield values adjusted for the three intensity levels in the different countries are available. Lower yields per area and therefore a higher land demand for minimum-use areas can increase their impact on biodiversity and vice versa for intense-use areas. Regarding the lower boundary of values, it should additionally be considered that minimum use is the least common intensity level globally (Chaudhary & Brooks, 2018). The shares the stages, sub-stages, and food categories have from the respective impacts in the uncertainty analysis either equal the values calculated in this study or differ at maximum with a value of 0.8 percentage points. Calculations in the aggregated unit result in a global potentially disappeared fraction of 1.67×10^{-3} for the biodiversity impact of AFW in Germany. The shares slightly differ from the values for vertebrate taxa in the non-aggregated unit and more for plants, which are weighted less than vertebrate taxa in the aggregated unit. The impact values for sub-stages and food categories from the uncertainty analysis and in the aggregated unit are listed in Tables S26 and S27 of SI S2.

Future studies monitoring AFW could improve the data basis by focusing directly on primary products instead of food categories. Additionally, more studies could apply and test the developed method of transferring animal products into single feed products. Concerning the characterization factors, Chaudhary and Brooks (2018) recommended their extension with further land use classes such as organic farms. The existing factors already allow for a differentiation after three intensity levels, which could be considered in future studies when information on yields and shares of intensities are available for the countries of origin. Besides land use, other environmental pressures such as climate change could additionally be considered. When aggregating the impacts, testing of different time scales concerning climate change could be useful, to illustrate how this affects the climate change impact compared to the shorter-term pressure of land use (Sanyé-Mengual et al., 2023).

4 | CONCLUSIONS

In this study, the biodiversity impact of AFW was quantified at the level of supply chain sub-stages and for different taxa for the first time. While households account for almost 50% of this impact, the large impact per mass of food services is remarkable, with individual catering reaching the same impact as one-person households. The applied methodology can be used as a blueprint for other countries using their individual data sets, for example, for transferring animal products on a level of single feed products in their countries of origin.

As a first political measure, households and individual catering could be informed further about their food waste's importance for biodiversity loss. In addition, environmental labeling schemes for food products should include biodiversity as one indicator as the impact differs largely between the food products. Products from pigs and cattle are not only responsible for over 50% of the impact from AFW but also have a large share of the impact from consumption. The results can also support measures aiming to conserve certain taxa, for example, avoiding bananas, cocoa, and coffee in food waste to conserve amphibians in tropical regions.

Complete prevention of AFW in Germany could potentially prevent 0.3 vertebrate and 1.5 plant species from becoming extinct. Further studies could confirm this impact for other industrialized countries and could examine it for developing countries. Additionally, the effectiveness of measures against food waste could be quantified, especially compared to measures aiming for a dietary change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article. Data on produced, processed, and consumed food product quantities, feed quantities, yields, and bilateral trade used in this study are provided by the Food and Agriculture Organization of the United Nations (FAO) and are openly available in the FAOSTAT database at https://www.fao.org/faostat/en/#data. Data on beverage consumption are provided by the German Federal Ministry of Food and Agriculture and are openly available in the statistical yearbook on nutrition, agriculture, and forestry, at https://www.bmel-statistik.de/fileadmin/SITE_MASTER/content/Jahrbuch/Agrarstatistisches-Jahrbuch-2017.pdf. Data on caloric and water contents of food products are provided by (1) the U.S. Department of Agriculture (USDA), being openly available in the FoodData Central database at https://fdc.nal.usda.gov/, by (2) INRA, CIRAD, AFZ, and FAO in the Feedipedia database at https://feedipedia.org/, and by (3) the literature source as referenced in the main text. Restrictions apply to the availability of detailed data on household food waste composition, which were used for this study under license from the German Federal Ministry of Food and Agriculture. Detailed data can be requested there, while aggregated data are available in the sources as referenced in the main text. Additional data on food waste mass and composition, feed demands, and species loss per area are available in the sources as referenced in the main text and the supporting information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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