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The environmental footprints of the feeds used by the EU chicken meat industry

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Abstract

Chicken meat production in the European Union (EU) causes environmental pressures within and beyond the EU, mostly due to feed consumption. The expected dietary shift from red to poultry meat will drive changes in the demand for chicken feeds and the associated environmental impacts, calling for a renewed attention on this supply chain. By performing a break-down analysis based on material flow accounting, this paper assesses the annual environmental burden caused within and outside of the EU by each single feed consumed by the EU chicken meat industry from 2007 to 2018. The increased feed demand required to support the growth of the EU chicken meat industry over the analyzed period caused a 17% increase in cropland use - 6.7 million hectares in 2018. Instead, CO_2 emissions linked to feed demand decreased by 45% over the same period. Despite an overall improvement in resource and impact intensity, chicken meat production was not decoupled from environmental burden. In 2018, 0.40 Mt of nitrogen, 0.28 Mt of phosphorous, and 0.28 Mt of potassium inorganic fertilizers were implied. Our findings indicate that the sector is not yet compliant with the EU sustainability targets defined in the Farm To Fork Strategy, calling for an urgent need to close existing policy implementation gaps. The EU chicken meat industry's environmental footprints were driven by endogenous factors such as the feed use efficiency at the chicken farming stage and the feed cultivation efficiency within the EU, as well as by exogenous factors such as the import of feed via international trade. Limitations on the use of alternative feed sources, as well as the exclusion of the imports from the EU legal framework constitute a crucial gap, which hamper fully leveraging existing solutions.

1. Introduction

Global meat consumption increased by 28% within the last decade (FAOSTAT, 2022), driven by the demand from growing and wealthier populations in developing countries (Clark et al., 2018) and favorable international trade agreements (OECD-FAO, 2022). Diverse dietary habits across the globe result in a heterogeneous displacement of multiple environmental burdens. The environmental burdens associated with chicken and pig meat mostly originate from their feeds, with over 50% of the overall greenhouse gas (GHG) emissions due to the feed cultivation phase for both meats (Gerber et al., 2013; MacLeod et al., 2013). Feed production requires large amounts of resources (Sporchia et al., 2021a) and is linked to significant levels of GHG emissions from land use and land use change (LULUC) (Caro et al., 2018; Osei-Owusu et al., 2021), as well as deforestation and peatland drainage (Pendrill et al., 2019a, 2019b). For instance, the feed demand from the EU pork industry is linked with 14.5 Mha of agricultural land, 1.9 Gm^3 of green water, 3.9 Gm^3 of blue water, 1.23 Mt of nitrogen, 0.35 Mt of phosphorous, and 0.34 Mt of potassium (Sporchia et al., 2021a). The inclusion of soybean in pig and chicken feed results in the emission of 9.38 kg of CO_2eq per kg of pig meat and 0.51 kg of CO_2eq per kg of chicken meat due to land use change (Caro et al., 2018). Moreover, 98% of the water footprint associated with broiler meat production is due to feed cultivation (Hoekstra, 2012) with similar patterns found for land use (Leinonen et al., 2012). In addition, the resource footprint linked to fertilizer application on land occurs exclusively in the feed cultivation phase (Leinonen et al., 2012).

The European Union (EU28 including the United Kingdom, hereafter EU) was the fourth largest chicken meat producer in 2018 (12 kt) accounting for 11% of global production (FAOSTAT, 2022). Despite a general decrease in meat consumption within the EU territory, the production of chicken meat in the region is expected to increase due to a growing foreign demand – especially from West African countries such as Ghana and Côte d'Ivoire, to which exports increased up to 230% over 10 years (European Commission, 2021a; Jakobsen and Hansen, 2020); meanwhile, the production of other meat types is forecasted to decline (European Commission, 2021b). The progressive shift from beef and pork to chicken meat is driven by the higher affordability and consumers' health benefits of this latter (European Commission, 2022; Willett et al., 2019). This shift will boost the EU chicken meat industry while restraining the pork and beef ones (European Commission, 2021c). However, this shift is not exempt from environmental issues. Indeed, this will bring about an increase in feed requirements (Kim et al., 2019) and related environmental burden as the EU's reliance on imported feeds (Kastner et al., 2011; Sporchia et al., 2021a; Taherzadeh and Caro, 2019) causes impacts and pressure (as defined in the DPSIR model) (OECD, 2003; Vanham et al., 2019) on both domestic and foreign ecosystems (Taherzadeh et al., 2021). Chicken meat production, for example, is linked with higher amounts of GHG emission from land use change compared to pork, and has similar amounts of GHG emission from feed compared to beef (Poore and Nemecek, 2018). Furthermore, increased poultry meat consumption will lead to higher use of pharmaceuticals and lower animal welfare levels (Resare Sahlin et al., 2020). This means that actions focusing on the chicken feed play a major role in ensuring an actual progress towards more sustainable diets in view of the future consumption trends.

Most of the existing environmental assessments of chicken meat production were limited to country- (Agri-footprint, 2015; Leinonen et al., 2012; Prudêncio da Silva et al., 2014; S G Wiedemann et al., 2017) and farm-scale analyses (Boggia et al., 2010; Cesari et al., 2017; Ellingsen and Aanondsen, 2006; González-García et al., 2014). Despite the informative potential of studies focusing on single or few environmental externalities (Elferink and Nonhebel, 2007; Krauß et al., 2015), assessments capturing the multifaceted nature of the environmental burdens associated with food production and consumption (e.g., simultaneous effects on water and land resources and climate change) provide more informative results, revealing insights and trade-offs that are helpful to address global sustainability challenges (Heinke et al., 2020; Sporchia et al., 2021b; Vanham and Leip, 2020).

As such, this study presents the first ever multi-dimensional environmental assessment of EU chicken meat feed during the period 2007-2018. Following a footprint family approach (Galli et al., 2012; Vanham et al., 2019), here we quantify the anthropogenic pressures on land, green and blue water, nitrogen, phosphorous and potassium resources, as well as the impacts on climate and water scarcity associated with the use of feeds in the EU chicken meat industry.

We reveal the feed consumption patterns of the EU chicken industry by performing a material flow analysis accounting for each feed item included in a feed mix that is representative for the EU-based chicken meat industry. The novel joint application of multiple footprint methodologies captures the underpinning global dependencies, thus tracking environmental pressures and impacts back to the country of origin (Fig. S1), allowing to identify the drivers of environmental burden and their variations over time. The global relevance, trade-driven interlinkages and trade-offs of the EU chicken meat industry are disclosed by considering country-specific and time-specific environmental efficiencies of 254 territories.

2. Methods

The full supply chain of the chicken meat industry is investigated, from the field cultivation of primary crops up to the broiler farm gate (Fig. S1). Differently from other animal systems (e.g., pig farming, see Sporchia et al., (2021a), chicken farming presents a pyramidal structure consisting of different generations of flocks dominated by purebred pedigree great grandparents, and ending with the broiler flocks (Mo et al., 2016). Parent flocks supply many broiler flocks throughout their whole lifetime (Hiemstra and Ten Napel, 2013). Consequently, feed is mainly used for broiler flocks rearing (Fig. S1).

As our aim is to track the environmental burden until the country of origin, we accounted for the cultivation of feeds in both EU member states (domestic) and in the Rest of the World (RoW). This phase covered all the components of the footprint family (land, water, and fertilizer) considered in the analysis. In a second phase, feed crops are processed to produce the final feed mix, which is commonly composed of primary (unprocessed) feed crops, refined products, or by-products derived from primary crops that underwent any kind of process (e.g., alcoholic distillation or oil extraction).

In this phase, the only resource required is blue water, necessary to mix the various ingredients. Finally, the broiler rearing phase is analyzed, in which day-old chicks, obtained from parental flock farms, are fed the feed mix from the second phase and raised until their maturity to reach the desired commercial live weight. Beside the feed, the broiler rearing phase requires drinking water for the birds and water supply for the farm services (e.g., for cleaning), both considered blue water, as in previous studies (Mekonnen and Hoekstra, 2010; Sporchia et al., 2021a). The achievement of the desired live weight for chickens is the downstream boundary of our study. Our focus is thus on the worldwide environmental pressures and impacts associated with the production of chicken meat within the EU, irrespective of where the chicken meat ends up being consumed. Accordingly, the environmental burden associated with the export of meat from chickens reared in EU farms is not included in the analysis. However, the environmental burden of final meat consumers could be easily calculated by coupling the results of the present analysis with import flows of countries importing chicken meat produced within the EU (see Figure S1).

To provide an assessment over time, we used annual data covering the period from 2007 to 2018. Croatia joined the EU on 1st July 2013, and EU accession has likely caused significant changes in the country's trade flows (e.g., in terms of commercial partners); however, as trade data (provided as annual aggregates) does not distinguish between the two semesters of the year, we considered Croatia as an effective member of the EU from 2014 onwards. This might limit the accuracy of our calculation for year 2013. Apart from this, the EU had 28 members, including the UK, throughout the whole period analyzed.

2.1 Feed composition and consumption

We estimated the feed composition and consumption following the approach adopted in previous studies (Sporchia et al., 2021a; zu Ermgassen et al., 2016). By using most recent available data (FAOSTAT, 2022) and considering recent studies, we based our estimation on EU data covering between 82% and 85% of the total chicken meat production (Tab. S1). The calculation was based on the weighted average volumes of EU physical broiler farming performances (Tab. S2) such as feed conversion ratio and liveweight at slaughter. Following Sporchia et al. (2021a), we filled data gaps by assigning physical performances of similar countries to the ones where information was lacking (Tab. S3).

The average broiler feed composition was estimated by using dietary data derived from studies on typical industrial broiler farming systems in the largest EU producers (Tab. S4). Since the feed mix is made of both primary products (e.g., cereal grains) and by-products (e.g., oil crop cake), we referred the calculation to primary products by applying product and value fractions retrieved from literature (Tab. S5) to convert by-products into primary products equivalents, as in previous studies (Mekonnen and Hoekstra, 2012; Sporchia et al., 2021a; zu Ermgassen et al., 2016). Crop production data was sourced from FAOSTAT (2022).

Hereafter we refer to land, water (green and blue), nitrogen, phosphorous and potassium use as resource use. In the same way we refer to resource use per ton of crop as resource use intensity.

The estimated average EU feed mix was composed by ~95% of crops and derived by-products considering the mass of the feed items as fed (Tab. S6). The remaining ~5% consisted of additives such as vitamins, minerals, amino acids and enzymes, or animal-based ingredients (e.g., fats and aquafeed). We assigned to these components of the diet the average of the resource use intensity of the crop-based components, since performing an accurate and rigorous estimation was not possible with the available data.

By using country-specific and year-specific data, we ensured that the analysis captures both the spatial and temporal heterogeneity of resource and impact intensities. For instance, each crop’s yield, specific water demand, impact on water scarcity, fertilizer demand, and CO_2 emission from land use change – for the field phase – and feed conversion ratio for each growing phase as well as final live weight – for the rearing phase (see Tab. S2, S3, S4, S5, S6, S7, S8 for details). However, water scarcity is only sensitive to spatial variability due to lack of time-specific data.

The annual EU physical performance (e.g., final live weight or feed conversion ratio) of the rearing phase was estimated through a weighted average based on country-level chicken meat production data (FAOSTAT, 2022) (see Tab. S1, S2, S3). However, FAOSTAT data does not distinguish between broiler and laying hens' meat, although laying hens' meat represents a marginal portion of chicken meat production in EU (Eurostat, 2021a). Consequently, we considered FAOSTAT chicken meat production data representative for broiler meat production. Having marginal presence in EU, backyard farming was excluded (Eurostat, 2021b).

2.2 Multiple resource use linked to chicken meat production

In this study we estimated the use of various natural resources (pressures) linked to the production of the feed mix for broilers reared within the EU. We focused on land, green water, blue water, and fertilizer use.

Agricultural land is classified in categories according to the specific type of exploitation it undergoes. It includes arable land and land for permanent or temporary crops, and pastures (FAOSTAT, 2022). According to the feed items included in the compiled broiler diet, our analysis includes both arable land (e.g., the land associated to cereal cultivation) and land for permanent crops (e.g., land occupied by oil palms). According to the Water Footprint Network (WFN) (Hoekstra et al., 2011), the volume of water required for crop cultivation can be divided into green water, blue water and grey water.

Green water is defined as the rainfall that is stored in soil; the blue water is the water abstracted from ground or surface water basins (Hoekstra et al., 2011); grey water is the water required to dilute polluted effluents to comply with legal limits, requiring effluent-specific data and detailed information on local policy to be estimated (Hoekstra et al., 2011).

The common fertilizers are non-metallic minerals, whose impacts are concentrated in the extraction and application phase (Oberle et al., 2019). They generally contain nitrogen, phosphorous or potassium, which are essential nutrients for plants. Various substances are available on the market, but commercial fertilizer formulations are commonly made of a mix of these nutrients. Phosphorous and potassium are mineral resources extracted from mines, whereas nitrogen fertilizer is sourced from air through energy intensive processes (Oberle et al., 2019).

2.2.1 Water use for broiler farming

We consider different sources for the calculation of the water use linked to broiler farming activity, following (Mekonnen and Hoekstra, 2012). We accounted for the water use for feed production (GW and BW for green and blue water, respectively), the water for services (SW) and the drinking water (DW). SW and DW are considered as blue water.

2.2.1.1 Water use for feed production

We used 2007-2018 annual crop production data to calculate the water used for producing feeds, following the approach used in previous analyses (Sporchia et al., 2021a, 2021c). For each producing country, crop and year, we estimated the Specific Water Demand (SWD, $m^3\ t^{-1}$) as the ratio between the Crop Water Requirement (CWR, $m^3\ ha^{-1}$), and the yield (Y, $t\ ha^{-1}$), as represented in equation 1:

$$\mathrm{SWD}_{c,n,a} = \mathrm{CWR}_{c,n}/\mathrm{Y}_{c,n,a} \tag{1}$$

where SWD indicates the specific water demand in country n in year a for crop c, CWR the water requirement of crop c in country n, and Y the yield of crop c in country n in year a. CWR were derived from Mekonnen and Hoekstra (2011). CWR data was assumed fixed since it mainly relies on climatic factors which are assumed to be constant for the period considered. Accordingly, we derived CWR values by using the average yield of the same period considered in the reference study (Mekonnen and Hoekstra, 2011) as shown in equation 2:

$$\mathrm{CWR}_{c,n} = \mathrm{SWD}_{c,n,96-05} \cdot \mathrm{Y}_{c,n,96-05} \qquad (2)$$

where SWD indicates the specific water demand in country n for crop c (Mekonnen and Hoekstra, 2011) and Y refers to the average yield of country n during the period 1996-2005 for crop c. Yield average data was retrieved from FAOSTAT (FAOSTAT, 2022). The data we used allowed to distinguish between green and blue water, as defined in the water footprint assessment manual (Hoekstra et al., 2011). Grey water footprint calculation requires specific data referred to the water body receiving the load of pollutants deriving from field run-off, to the water body chemical characteristics and to local policy (Hoekstra et al., 2011). Although previous assessments adopted a fixed global or regional run-off rate and a fixed global acceptability limit for the concentration of pollutants, we chose to exclude grey water calculation from this study to maintain the country-specific approach. However, previous assessments revealed that, for the feed crops considered, the grey component of the water footprint represents the smallest share of the total water footprint (Mekonnen and Hoekstra, 2011): for none of the crops included in the estimated diet, grey water footprint is higher than 20% of the total water footprint at global level (Mekonnen and Hoekstra, 2011). Aside from the water directly used to feed crops cultivation, a certain amount of water is used to produce concentrate feed (Mekonnen and Hoekstra, 2010). Following Chapagain and Hoekstra (2003), the water use for feed mixing was assumed to be 50% of total concentrate feed intake (or 0.5 m^3 per ton of concentrate feed intake) (Mekonnen and Hoekstra, 2012). The total amount of concentrate feed was estimated following the definition of concentrate feed and roughage, as done in previous studies (Mekonnen and Hoekstra, 2010) (Tab. S5). The water use for feed mixing was assumed to be blue water as it was done in the same study.

2.2.1.2 Drinking and servicing water use

Since recent studies providing drinking and servicing water use data for the EU countries cover a very low share of the total EU production, we followed (Chapagain and Hoekstra, 2003; Mekonnen and Hoekstra, 2010) for their estimation. Since only weight-based data is available (with info missing on the average slaughtering age), we assumed that broilers are 5.5 weeks old when slaughtered, using a conservative approach. Indeed, broilers' age at slaughter ranges between 5 and 8 weeks for most commercial broiler breeds, although, due to efficiency maximization needs, it tends to be as low as possible. As calculations are provided on a per animal basis, we estimated the drinking and servicing water use by using the EU yearly average broiler weight at slaughter (Tab. S2). Accordingly, we obtained the average value of drinking and servicing water use per unit of chicken meat produced. Both drinking and servicing water use are considered blue water, namely, deriving either from the municipal aqueduct or from on-site wells.

The green SWD corresponds to the green water use intensity, whereas the sum of the blue SWD and the concentrate feed mixing, drinking, and servicing water use corresponds to the blue water intensity.

2.2.2 Land use for feed production

Following the approach of previous studies (Nguyen et al., 2011; Reckmann et al., 2013; Sporchia et al., 2021a), we accounted for the land use directly linked to feed production, considering chicken farming 'landless'. Accordingly, we considered the area occupied by the buildings and facilities belonging to the farms as negligible.

For each feed item associated with the EU broiler diet, the associated land use (LU) was estimated by means of harvested area data from FAOSTAT (FAOSTAT, 2022). The analysis captures the existing global diversity in terms of land use efficiency by using country-scale, crop-specific yield data for 254 territories. The reciprocal of the yield is used as an indicator of efficiency, namely, land use intensity (LI).

2.2.3 Fertilizer use for feed production

To estimate the use of fertilizer linked to the broiler feed production, for each crop and country, the country and crop specific fertilizer use intensity (FI) was estimated by using crop- and country-specific data on fertilizer use and crop- and country-specific production data.

The present analysis focuses on the inorganic fertilizers, thus excluding the nutrients deriving from organic inputs such as manure and sewage sludge (and the respective derivatives such as digestate and ashes). It is fundamental to highlight that the use of inorganic fertilizers in the countries providing the feed crops could lead to nutritional impoverishment and soil exhaustion, whereas within the EU – where organic inputs are largely used together with inorganic ones – soils might be overloaded with nutrients, with significant losses. Therefore, the international trade of soil nutrients-intensive products disrupts the normal nutrient cycles (Zhao et al., 2021) with the present case study representing the effects of a one-way system.

We estimated the FI of each crop as the ratio between fertilizer use data and crop production data retrieved from FAOSTAT (2022), as shown in equation 3:

$$\mathrm{FI}_{\mathrm{c,n,a}} = \frac{\mathrm{FU}_{\mathrm{c,n,a}}}{\mathrm{P}_{\mathrm{c,n,a}}} \tag{3}$$

Where FI indicates the fertilizer intensity for each crop c in country n, and year a, FU indicates the total fertilizer use for crop c in country n and year a, and P indicates the total production of crop c in country n, in year a. Available data allowed to estimate, individually, the nitrogen, phosphorous and potassium intensity per ton of each feed item.

Data on the total amount of fertilizer use by crop (or crop group) and by country was available for 2007 (IFA, 2009), 2010 (IFA, 2013), and 2014 (IFA and IPNI, 2017). Accordingly, we first calculated FI for each country for the available years and then applied the compound annual growth rate (CAGR) to estimate the FI for the missing years (Tab. S7). Available data covered most of the global production for each crop (Tab. S7). No data for single EU Member State was available, as only aggregated EU data was provided. However, this matches the data requirement for the scope of this study. For few crops, the fertilizer use values were available only as aggregate (e.g., “other oil crops” for rapeseed and sunflower seed). In such cases we used the corresponding aggregate item available (Tab. S8).

2.3 Tracing the origin of the feed

The feeds consumed in EU broiler farms originate in both EU and extra-EU countries. Consequently, the present analysis is designed to capture and reveal the global dependencies that underpin the EU chicken meat sector. As such, the origin of each single feed item included in the broiler diet was traced, following international trade pathways across 254 territories. However, data limitations impeded to accurately estimate the trade-related impacts, such as CO_2 emission linked to international (and national) transport, which were previously found to be marginal compared to the overall impact (MacLeod et al., 2013). We used FAOSTAT (2022) annual crop production and COMTRADE (UN Statistics Division, 2022) data obtained via Chatham House (2022), and applied Kastner et al. (2011) data treatment approach to link producers to final consumers, avoiding double counting of re-export. This operation allows to apply country-specific resource use intensities to trade flows. Since the aim of this operation was to trace the origin of each feed item, we applied mass equivalence factors to convert secondary products (such as agricultural by-products) into primary crops equivalent. Accordingly, the mass balance is respected. The applied mass conversion factors were sourced from various studies (see Tab. S5). Conversely, to account for the different economic values among the secondary products originating from the same crop (e.g., soybean oil and cake), we adopted an economic allocation approach to estimate the resource use intensities of each feed item. This ensures that the resource use balance is respected. As for the mass factors, economic allocation factors were sourced from different sources (Tab. S5). Overall, the diversity among the resource use intensities of each country that exported to (or produced in) the EU any of the feed item considered (Tab. S5) is taken into account.

For each feed item (primary equivalents) and year, we compiled a detailed bilateral trade matrix showing import and export quantities among 254 countries/territories (see Tab. S9 and supplementary material SM2).

2.4 Estimation of virtual resource use trade

The virtual resource use trade (VRUT) corresponds to the crop-specific resource use linked to the amounts of crop produced for being exported. The VRUT of country n is estimated by multiplying the traded crop (TC) by its resource intensity (RI) as follows in equation 4:

$$VRUT_{c,ne,ni} = TC_{c,ne,ni} \times RI_{c,ne} \tag{4}$$

VRUT refers to the resource use originated in the exporting country ne, and transferred to the importing country ni, for the cultivation of crop c. The trade flows (TC) represent the quantity of crop traded by exporting country ne to the importing country ni. Trade data was extracted from COMTRADE (UN Statistics Division, 2022). RI correspond to the resource use intensities, as detailed in section 2.2.

By applying the data treatment proposed by Kastner et al. (2011), each trade flow directly links producers with final consumers, avoiding the issues created by re-export flows. Accordingly, the trade balance among virtual resource use is respected and the final consumption equals the sum of the total production plus the imports minus the exports.

2.5 Multiple impact assessment

The environmental pressures represented by the natural resource use can turn into a range of environmental impacts causing environmental burden according to where and when the pressures happen (DPSIR model) (OECD, 2003; Vanham et al., 2019). Policies addressing environmental matter should address both pressures and impacts to be effective (Vanham and Leip, 2020).

Therefore, having tracked the displacement of the environmental pressures, we were able to estimate part of the environmental impacts by adopting the methodologies described in the following sections.

2.5.1 Water scarcity footprint assessment

To link the environmental pressures to the environmental impacts for the use of blue water, we estimated the water scarcity footprint (WSF) by applying the approach proposed by Boulay et al. (2018) and used country- and crop-specific factors provided by Boulay et al. (2019). The concept of available water remaining assumes that freshwater withdrawals can result in potential water deprivation for either the ecosystems or human activities (Boulay et al., 2018). Following previous studies (Schestak et al., 2022; Zucchinelli et al., 2021), we applied water scarcity factors to the blue water consumption to reveal the total water scarcity linked to each single feed item, according to its origin as shown in eq. 5:

$$\mathrm{WS}_{\mathrm{c,n,a}} = \mathrm{BW}_{\mathrm{c,n,a}} \cdot \mathrm{SF}_{\mathrm{c,n,a}} \tag{5}$$

where WS indicates the specific water scarcity in country n in the year a for crop c, BW the blue water volume required for crop c in country n and SF the water scarcity factors of crop c in country n in the year a. BW is estimated using SWD values calculated as described in eq. 1. The water scarcity (WS) assessment attributes higher or lower value to freshwater use from regions where there is, respectively, less or more water remaining per area compared to the world average, expressed in world equivalent m^3 (world eq.) (Boulay et al., 2018). SF data were sourced from Boulay et al. (2019). Due to the limited data availability, we performed the water scarcity analysis only for the last year of the time series (2018).

2.5.2 Estimation of the CO_2 emission from land use change

In terms of GHG emissions, the study focuses on CO_2 emission from LULUC (CO_2 largest source (MacLeod et al., 2013)), excluding less significant gases (CH_4 or N_2O) and sources (e.g., direct energy use) (MacLeod et al., 2013; Sandström et al., 2018), due to data limitations. Although this would provide even further precious information, we made this choice because a global database providing all the necessary crop-specific and time-specific information to estimate the CH_4 (e.g., from manure management) or N_2O (e.g., from manure management or fertilizer application) at country scale is not available. Nevertheless, an accurate estimation of the fertilizer application – as the one provided here – could be helpful to identify strategies to reduce the use which, in turn, could lead to reduced N_2O emission (Meng et al., 2023). To assess the CO_2 emissions due to land use change linked to the production of chicken feeds, we rely on a recently published dataset (Pendrill et al., 2020). This dataset combines satellite observations of ongoing deforestation with a land-balance model that attributes deforestation to crops expanding into forested areas (Pendrill et al., 2019a). In a further step, data on deforested areas is combined with estimates of biomass carbon stocks to assess the CO_2 emissions induced by land conversions (Pendrill et al., 2019b). This results in country-, year- and crop-specific estimates of the CO_2 emission linked to deforestation for 153 countries, i.e., all countries where agricultural expansion is thought to drive ongoing deforestation. As we do in this study, this data on land use change also follows the product and country definition of FAOSTAT (2022) and is thus straightforward to integrate in our estimates, with the caveat that data is presently only available up to 2017 (as compared to 2018 for the rest of the data used in this study). It is necessary to clarify that CO_2 emission allocation to cropland (and, ultimately, to crops) requires a careful assumption. Indeed, since this kind of indirect CO_2 emission does not occur simultaneously to deforestation and peatland oxidation is not immediate, it is necessary to define an amortization period over which the estimated emission is spread, and, in turn, allocated to the crops produced throughout the same period. There is no general agreement on the amortization period and the arbitrariness of the choice is currently unavoidable (Cederberg et al., 2011; Hörtenhuber et al., 2014; Persson et al., 2014; Ponsioen and Blonk, 2012). In our case, the amortization period considered is 10 years, which is also consistent with the temporal scale of the analysis presented in this paper.

3. Results

3.1 Global environmental pressures and their displacement

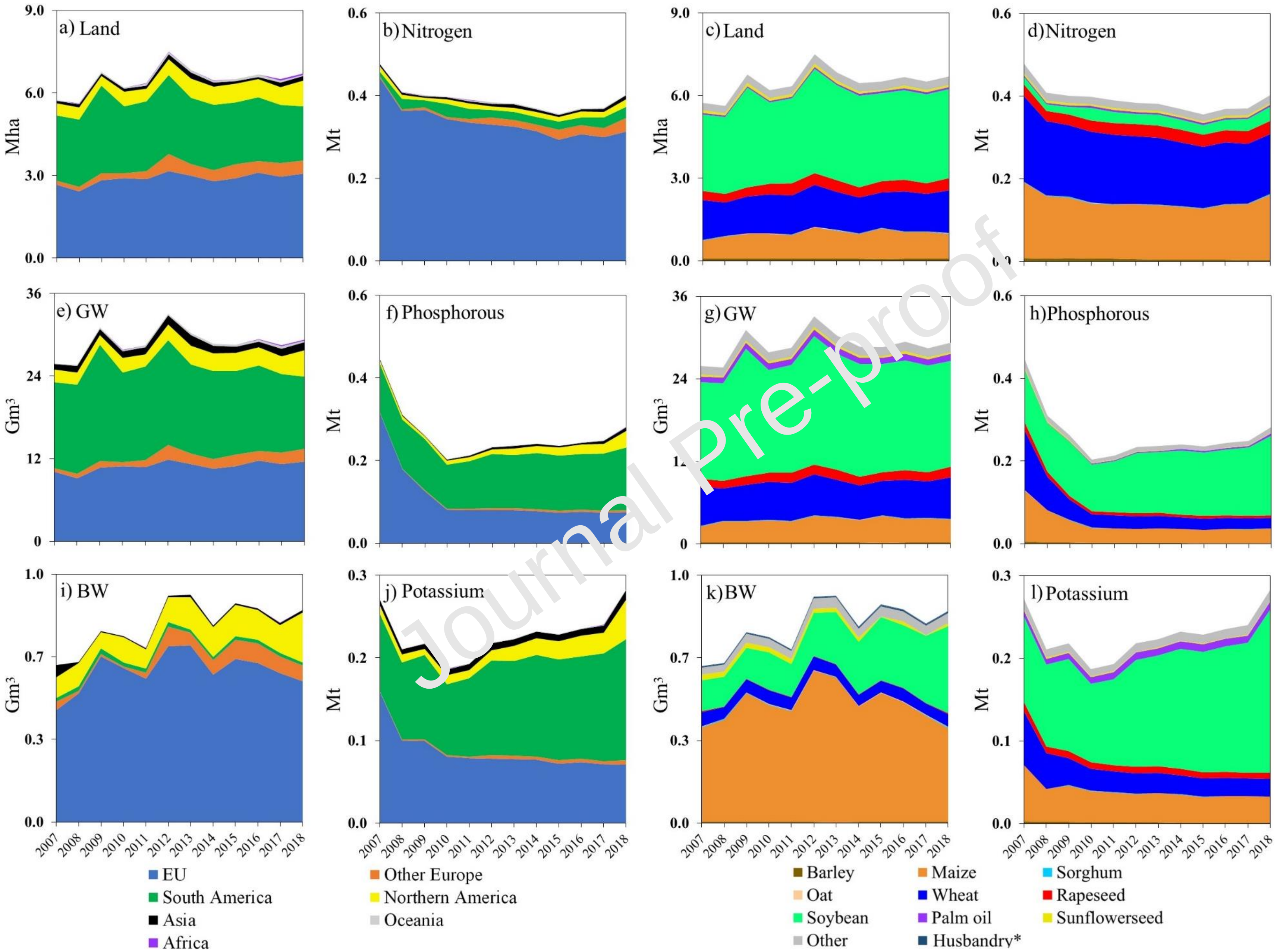
a) Land
b) Nitrogen
c) Land
d) Nitrogen
e) GW
f) Phosphorous
g) GW
h) Phosphorous
i) BW
j) Potassium
k) BW
l) Potassium
Mha
Mt
Gm³
9.0
6.0
3.0
0.0
0.6
0.4
0.2
36
24
12
0
1.0
0.7
0.3
0.1
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
EU
South America
Asia
Africa
Other Europe
Northern America
Oceania
Barley
Oat
Soybean
Other
Maize
Wheat
Palm oil
Husbandry*
Sorghum
Rapeseed
Sunflowerseed

Figure 1. The total resource use required to satisfy the EU chicken meat industry demand for chicken feed, by area of origin (a, b, e, f, i, j, on the left) and primary feed crop (c, d, g, h, k, l, on the right). *Husbandry refers only to blue water (BW) and aggregates Drinking Water (DW), Service Water (SW), and Mixing Water (MW).

While chicken meat production in the EU grew by 35% (2008-2017) (FAOSTAT, 2022), cropland use increased by 17% reaching 6.7 million hectares (Mha) in 2018 (Fig. 1). The cropland necessary to feed the EU chicken meat industry accounted for ~0.5% of the global or ~5% of the EU cropland (FAOSTAT, 2022). This area corresponds in size to Ireland's land area (World Bank, 2022), although most of such cropland was exploited outside the EU (Fig. 1a). Figure 1c reveals the feed items responsible for most of the land use to be soybean (48-53%), wheat (20-25%) and maize (11%-17%). The two peaks identified for land (Fig. 1a-1c) and green water use (GW) (Fig. 1e-1g) are due to low yearly crop yields for South American (SA) soybeans (Paraguay -41% and -50%, Argentina -35% and -12%, and Brazil -6% and -10% in 2009 and 2012, respectively, compared to the previous year) and for EU-based maize (-20% in 2012 compared to 2011) (FAOSTAT, 2022).

GW - the water stored in soil potentially available for uptake by plants - showed a similar trend (Fig. 1e-1g), with an overall 13% increase (from 25.9 Gm^3 in 2008 to 29.3 Gm^3 in 2018). The volume of GW exploited to feed the EU chicken meat industry accounted for ~0.4% of the global GW use (Hoekstra and Mekonnen, 2012) and mainly occurred outside the EU (60-66%). Soybean (53-60%), wheat (17-22%), and maize (9-14%) again drove GW use (Fig. 1g).

The use of surface freshwater and groundwater (blue water - BW) within the EU chicken meat industry increased most strongly (+35% from 0.6 Gm^3 in 2007 to 0.9 Gm^3 in 2018) among the resources considered (Fig. 1i-1k). The annual average volume of exploited BW accounted for ~0.1% of the global BW use (Hoekstra and Mekonnen, 2012). Unlike other resources, BW was mainly sourced from within the EU (66-87%, Fig. 1i). As shown in Figure 1k, BW use was mainly linked to maize (ranging 41-63%), soybean (15-38%), and wheat (5-8%). BW for uses other than irrigation was sourced in EU and remained below 6% without a definite trend (Fig. 1k).

Nitrogen use decreased by nearly 16% (0.48-0.40 Mt), mostly between 2007 and 2008 (Fig. 1b-1d). It accounted for 0.4% of the global nitrogen use (FAOSTAT, 2022). Nitrogen use mainly occurred in EU territories (78-93%), while a minor part was outsourced (Fig. 1b). Most of it was used for the cultivation of maize (33-39%), and wheat (36-44%) used in chicken feeds production, followed by rapeseed (6-8%) and soybean (4-9%) (Fig. 1d). Indeed, cereals are mainly domestically consumed within EU, and only marginally imported.

Phosphorous use in the EU chicken meat industry recorded an overall decrease (-36%), passing from 0.44Mt in 2007 to 0.28Mt in 2018 (Fig. 1f-1h), and corresponding to 0.6% of the global phosphorous use (FAOSTAT, 2022). Most of it was outsourced throughout the whole period (52-72%), except for 2007-2008 (29% and 42%, respectively) (Fig. 1f). Phosphorous was mainly used in the feed industry for the cultivation of soybean (28-68%), maize (13-28%) and wheat (9-32%) (Fig. 1h). Meanwhile, potassium use recorded an overall increase (4%, 0.27-0.28 Mt) (Fig. 1j-1l) covering 0.7% of the global use (FAOSTAT, 2022). It was mainly outsourced (52-75%), except for 2007 (41%) (Fig. 1j). Potassium was mostly used outside the EU, for soybean (38-70%), maize (11-25%), and wheat (8-24%) cultivation (Fig. 1l). The initial decrease in fertilizer use was linked to the global increase in prices due to the 2008 financial crisis (European Commission, 2019a) and to a reduced meat demand (Eurostat, 2021a).

Overall, the recorded trends indicate that the amount of resource use for chicken feed production is not yet totally decoupled from the quantity of chicken meat production. Moreover, the trends indicate an increasing reliance on the externalization of resource use outside the EU boundaries.

Considering the EU fair share of resource use in 2018 derived from the planetary boundaries approach, we found that the EU chicken meat industry accounted for about 68% and 10% of EU fair share of phosphorous and nitrogen fertilizer use, respectively (Steffen et al., 2015). In the same year, poultry meat (predominantly chicken) in the EU only provided around 8% of the protein and 2.3% of the energy supplied to EU residents' diet (FAOSTAT, 2022). EU pork meat, already deemed as less sustainable, covered a more than three times larger share of phosphorous and nitrogen EU-assigned planetary boundaries – 296% and 27%, respectively – while providing a less than three times larger share of protein and energy supply to the EU human diet – 11% and 6.3% respectively, compared to chicken (FAOSTAT, 2022; Sporchia et al., 2021a; Steffen et al., 2015).

3.2 Global environmental impacts and their displacement

3.2.1 The impact on climate change

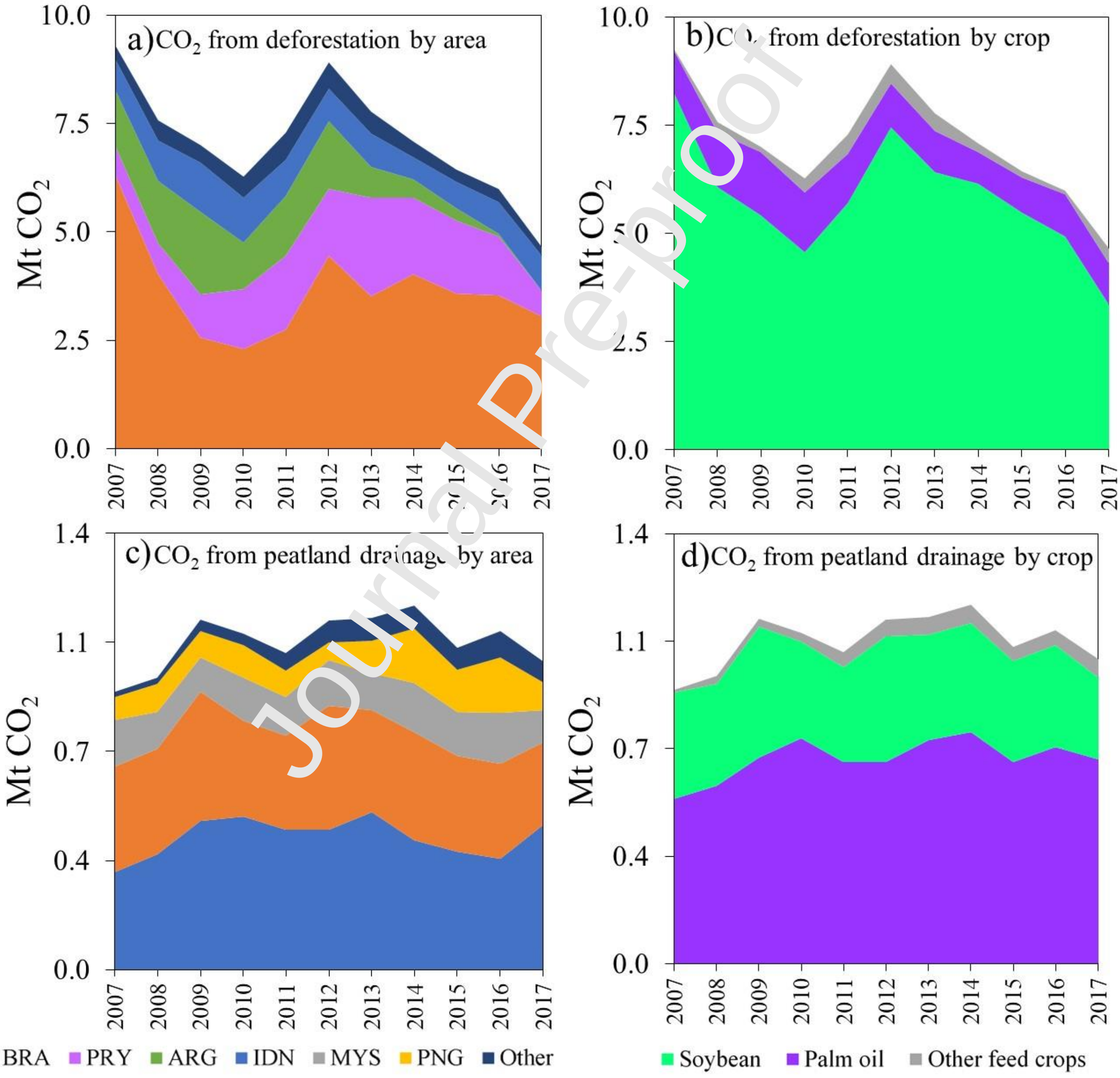

Figure 2. Trends in the CO_2 emissions linked to deforestation (a, b) and peatland drainage (c, d) bound to the cultivation of chicken feeds used in the EU chicken meat industry, by country of origin (a and c) and feed type (b and d). As soybean and palm oil accounted for most of the emissions, the other feed items have been aggregated. BRA = Brazil, PRY = Paraguay, ARG = Argentina, IDN = Indonesia, MYS = Malaysia, PNG = Papua New Guinea.

CO_2 emissions from LULUC due to feeds production for EU chicken meat industry recorded a significant (44.6%) decrease (from 9.3 Mt in 2007 to 4.6 Mt in 2017) over the studied period (Fig. 2a). This was associated with an opposite trend in chicken meat production (Eurostat, 2021a) indicating a decreasing carbon intensity (t CO_2 per t of meat) for EU chicken meat. The estimated emission corresponds to 0.11% of the global CO_2 emissions from LULUC in 2017 (FAO, 2020). As shown in Figure 2a, most of the CO_2 emissions from deforestation (ED) originated in South America (SA) throughout the whole period analyzed, covering 76-89%. CO_2 emissions initially decreased, then grew in 2011 and peaked in 2012 (Fig. 2a-2b) due to the import of feed items – with soybean accounting between 72% and 89% (Fig. 2b) – from SA (Fig. 2a). This was specifically due to a peak in the intensity of soybean from Paraguay, the most carbon-intensive among the top providers, and Brazil (fig 2e-2f), linked to low soybean yields. Palm oil cultivation also contributed to CO_2 emissions (10-22%), throughout the whole period analyzed.

Emission from peatland drainage (EPD) differed significantly from ED (Fig. 2c-2d). First, EPD grew by 11% (0.89-0.99 Mt). Second, most of it originated in Asian countries (48-58%) (fig 2c). Third, palm oil was the main source (53-68%), followed by soybean (27-39%) (Fig. 2d).

EPD trends follows the trends of resource use shown above, indicating that a complete decoupling from chicken meat production has not yet been achieved. Instead, ED trends clearly indicate a progress towards decoupling, especially after 2012. Differently from resource use, the emission from LULUC is linked almost exclusively to feed production outsourced to countries beyond the EU boundaries.

3.2.2 The impact on water scarcity

Freshwater withdrawals can result in potential water deprivation for the ecosystems or human activities (Boulay et al., 2018). Accordingly, it is fundamental for policy makers and water managers to ensure a proper allocation since trade-offs arise due to the current levels of blue water use (Vanham et al., 2021). In 2018, the total impact on WS reached 17 world eq. Gm^3. This amount indicates that such blue water use has about 20 times higher potential to deprive another user (human or ecosystem) of water use on a global average (see Boulay et al. (2018) for further details). It was mainly due to maize (58%), soybean (21%), and wheat (13%) (Fig. 3d). The largest volumes of BW (the one causing water scarcity) were linked to the same crops in the same order, but with remarkable differences (47%, 43% and 7%) (Fig. 3c). The largest impact was created within the EU (75%), followed by North America (NA) (17%) (Fig. 3b).

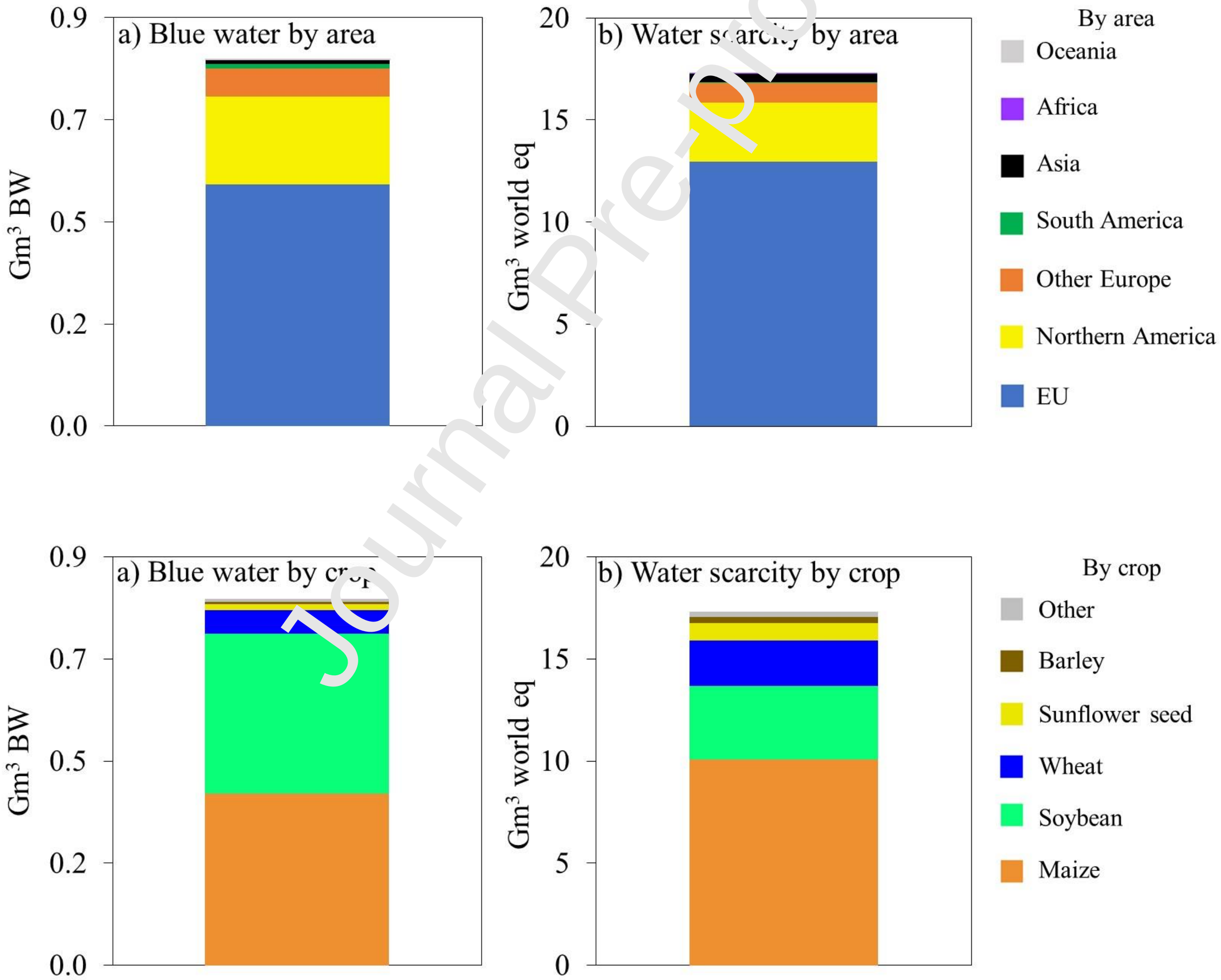

Figure 3. The global displacement of blue water (BW) use (a, c) required to produce chicken meat in the EU in 2018 and the related water scarcity (WS) (b, d), by continent of origin (a and b) and single primary feed crop (c and d). Feed crops with overall significance lower that 1% have been aggregated into the "Other" category. To allow comparison among feed crops, these amounts exclude the blue water from the rearing phase and the one attributed to "other" feed items.

However, the share of BW exploited within the EU was lower (64%) compared to WS. Conversely, the relevance of NA (25%) for BW was higher compared to WS (Fig. 3a). Our results indicate that actions aiming to mitigate the impact on WS should mainly focus on the feed domestically sourced. The WS footprint for chicken feed use in the EU covered ~3% of the WS embodied in EU agricultural imports (Dolganova et al., 2019).

3.3 The environmental profile of broiler diet ingredients

As shown in table 1, intensities (amount of resource/impact per ton of feed produced) largely vary among different feed items. Moreover, the resource intensities of EU-sourced feeds were frequently lower than those of the imported feeds. Between 2007 and 2018 such frequency grew. The environmental profile of the broiler diet reflected directly on the environmental profile of the derived chicken meat: in terms of environmental pressure, 1 kg of chicken meat (carcass weight) produced in the EU in 2018 was linked to 5.6 m^2 of land, 2.4 m^3 of green water, 71.4 dm^3 of blue water, 33.5 g of nitrogen, 23.5 g of phosphorous, and 23.6 g of potassium; meanwhile, the same quantity of chicken meat was linked to 1443 global eq. dm^3 in terms of impact on water scarcity, and to 395.7 g and 84.5 g of CO_2 emissions in terms of global warming potential from deforestation and peatland drainage, respectively (see Tab. S10, S11). The intensities decreased over time for most crops, with the remarkable exception of soybean and palm oil in terms of nutrients and BW. This indicates that a careful selection of foreign providers of such crops – mainly imported – could be crucial to facilitate the reduction of the overall intensity of the chicken feed mix.

Table 1. Overall intensities for each feed item consumed by the EU broiler industry in 2007 and 2018. The intensities are shown also by origin. Feed items are expressed as primary commodity equivalent. Palm oil was only imported. *CO_2 emissions refer to 2017. Water scarcity intensity was estimated only for 2018. GW = Green Water, BW = Blue Water, N = Nitrogen, P = Phosphorous, K = Potassium, ED = CO_2 from deforestation, EPD = CO_2 from peatland drainage, WS = water scarcity.

		2007								2018								
	Resource or impact	Land	GW	BW	N	P	K	ED	EPD	Land	GW	BW	N	P	K	WS	ED*	EPD*
	Unit of measure/t feed	ha/t	m^3/t	m^3/t	kg/t	kg/t	kg/t	kg/t	kg/t	ha/t	m^3/t	m^3/t	kg/t	kg/t	kg/t	m^3 w. eq./t	kg/t	kg/t
Barley	Import	0.59	1856	45	11	5.0	1.8	22	1.46	0.39	1192	24	9.9	2.2	1.6	952	0.11	2.7
	EU	0.24	634	14	25	16	9.3			0.22	579	12	8.7	1.5	1.7	3048		
	Overall	**0.24**	**639**	**14**	**25**	**16**	**9.3**	**0.2**	**0.01**	**0.22**	**584**	**12**	**8.7**	**1.5**	**1.7**	**3027**	**<0.01**	**0.03**
Sorghum	Import	0.28	1004	50	19	6.1	2.4	232	538	0.33	1328	51	32	10	3.5	13	0.04	0.1
	EU	0.18	582	7.4	32	22	8.5			0.19	620	8.9	8.8	1.5	1.7	93		
	Overall	**0.26**	**921**	**42**	**22**	**9.3**	**3.6**	**75**	**173**	**0.26**	**970**	**30**	**20**	**5.7**	**2.6**	**67**	**0.01**	**0.02**
Wheat	Import	0.44	1673	51	21	7.2	2.3	16	4.2	0.35	1338	29	22	5.8	2.9	782	4.1	11
	EU	0.21	820	6.4	32	23	10			0.19	723	5.3	18	3.1	2.7	233		
	Overall	**0.22**	**867**	**8.9**	**32**	**22**	**10**	**1**	**0.2**	**0.19**	**755**	**6.6**	**18**	**3.2**	**2.7**	**254**	**0.3**	**0.4**
Maize	Import	0.18	575	246	17	5.3	5.9	3	5.1	0.14	558	35	16	3.2	3.6	771	216	14
	EU	0.11	403	56	33	22	12			0.12	426	59	24	5.7	4.8	2464		
	Overall	**0.12**	**413**	**67**	**32**	**21**	**12**	**1**	**1.1**	**0.13**	**464**	**53**	**22**	**5.0**	**4.4**	**2095**	**47**	**3.1**
Oat	Import	0.49	1378	113	17	7.3	1.3	61	54	0.52	1763	67	9.4	2.9	3.9	4705	282	41
	EU	0.34	839	143	22	19	14			0.35	879	170	8.8	1.5	1.7	12,276		
	Overall	**0.34**	**840**	**143**	**22**	**19**	**14**	**0.03**	**0.03**	**0.35**	**880**	**169**	**8.8**	**1.5**	**1.7**	**12,272**	**0.2**	**0.02**
Rapeseed	Import	0.73	3238	19	21	6.6	4.4	34	0.8	0.51	2135	0.5	24	5.5	5.3	0.03	26	146
	EU	0.35	1124	2.5	34	23	13			0.34	1154	2.9	27	5.4	6.4	17		
	Overall	**0.38**	**1288**	**3.3**	**33**	**22**	**13**	**7**	**0.2**	**0.37**	**1325**	**2.5**	**27**	**5.4**	**6.2**	**14**	**5.6**	**31**
Soybean	Import	0.36	1821	10	1.7	16	13	1411	59	0.33	1612	22	3.9	21.3	22	213	383	30
	EU	0.45	1744	297	32	18	13			0.34	1329	193	0.4	3.8	6.3	1123		
	Overall	**0.36**	**1819**	**16**	**2.4**	**16**	**13**	**1295**	**54**	**0.33**	**1589**	**36**	**3.6**	**19.9**	**20**	**288**	**352**	**28**
Sunflower seed	Import	0.79	2917	50	8.5	4.6	2.0	80	1.2	0.47	1599	15	15	3.8	3.3	508	0.1	0.2
	EU	0.62	1999	167	39	25	11			0.41	1351	98	28	5.4	6.5	6236		
	Overall	**0.66**	**2215**	**139**	**31**	**20**	**8.9**	**26**	**0.4**	**0.43**	**1430**	**72**	**24**	**4.9**	**5.5**	**4336**	**0.03**	**0.1**
Palm oil	Import	0.06	834	<0.01	4.2	1.6	7.5	507	278	0.06	863	<0.01	4.0	5.2	8.4	<0.01	833	584

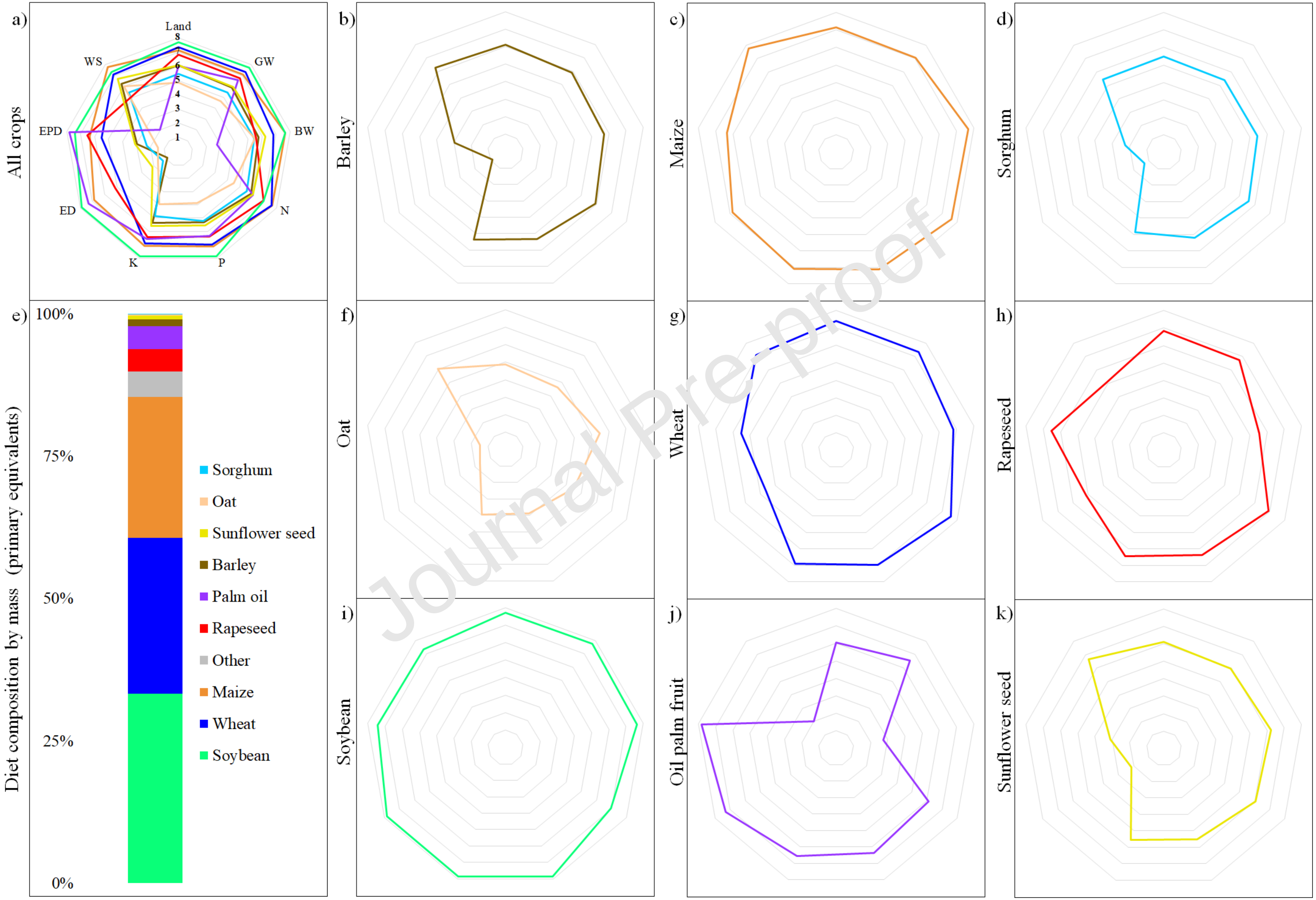
a)
All crops
Land
GW
BW
N
P
K
ED
EPD
WS
1
2
3
4
5
6
7
8
b)
Barley
c)
Maize
d)
Sorghum
e)
Diet composition by mass (primary equivalents)
100%
75%
50%
25%
0%
Sorghum
Oat
Sunflower seed
Barley
Palm oil
Rapeseed
Other
Maize
Wheat
Soybean
f)
Oat
g)
Wheat
h)
Rapeseed
i)
Soybean
j)
Oil palm fruit
k)
Sunflower seed

Figure 4. A radar chart to compare feed items (expressed in primary equivalents) in terms of both environmental pressures and impacts of the overall diet. GW = Green Water, BW = Blue Water, N = Nitrogen, P = Phosphorous, K = Potassium, ED = CO_2 from deforestation, EPD = CO_2 from peatland drainage, WS = water scarcity. a) shows an overlapping representation of the charts for the single feed items. e) facilitates the interpretation of the charts by providing an overview of the contribution of each feed item to the overall diet in terms of mass (details in Tab. S6). The concentric polygons are sorted from the innermost to the outermost in an increasing order according to the pressure/impact level, with a logarithmic scale. The sum of all item's absolute values has been normalized over 10^8 for each impact/pressure. The radial axis is expressed in an exponential scale with base 10 (see a) due to the large magnitude of the variability among the values for different feed items. The reference year is 2018, except for CO_2 from deforestation and peatland drainage, for which the reference year is 2017.

Figure 4 shows that the environmental pressures and impacts associated with each feed item of the EU broiler diet vary within a wide range of values. The most relevant feed crops in terms of mass (see Tab. S6) account for a large share of environmental burden compared to the other crops. However, palm oil's relevance in terms of EPD (the highest) (Fig. 4g) reveals that although this feed crop has a marginal mass relevance (within the feed mix), it noticeably contributes to GHG emissions. Palm oil is exclusively imported since there is no EU-based production, unlike soybean. This reveals an intrinsic exposure of the EU chicken meat sector due to a complete dependence on import, with related risks (Shigetomi et al., 2020). In turn, this result stresses how the related pressures and impacts, which are not negligible, are exclusively externalized (i.e., caused far away from the place of consumption), with consequences for this kind of remote exploitation that go beyond the mere environmental domain (Tang and Al Qahtani, 2020) and are directly driven by EU demand.

4. Discussion

The EU chicken meat industry causes significant environmental burden both within and beyond the EU borders (Fig. 1,2,3). In some cases, impacts are predominantly externalized: phosphorous footprint and GHG emissions from LULUC, for instance, mostly derive from imported feed (Fig. 1,2). The EU Farm To Fork Strategy targets domestic crops' cultivation but overlooks the role of imported feeds, which we show being remarkable in terms of environmental burden. Our results highlight the critical gap in this kind of policies suggesting that accounting for the import is crucial.

Nonetheless, a noticeable reduction in pressure and impact intensities has been recorded (Tab. 1), which has led to a general decrease of the total footprints over time (Fig. 1, 2) and was driven by three factors. First, a general improvement in the feed cultivation efficiency, which directly affects the intensities of the feed crops with similar repercussions on the overall chicken diet (Tab. 1, Fig. 4). Second, a progressive reduction in the reliance on imported feed crops in favor of domestic production, generally characterized by lower intensities. For instance, the gradual reduction of imported soybean followed the gradual increase in supply within the EU (FAOSTAT, 2022), characterized by lower intensities (Tab. 1). Third, the progressive reduction of the feed conversion ratio (FCR, t feed / t meat) (Tab. S9) obtained through technological advancements at the rearing phase, which resulted in a transversal reduction of the chicken meat pressure and impact intensities (unit of pressure or impact per kg of chicken meat). Our findings are in line with recent literature (Bai et al., 2021; Qian et al., 2018; Zhao et al., 2021).

Despite the improvement in terms of intensities, a complete decoupling between the environmental burden and the chicken meat production has not yet been recorded. Nevertheless, gradual improvements allowed to save significant amounts of resources and avoid remarkable amounts of impacts. For instance, if 2018 EU chicken meat production had been obtained through the consumption of feed with the intensities of 2007, further 1.1 Mha of land, 5.7 Gm^3 of green water 1,158 thousand m^3 of blue water, 244 kt of nitrogen, 318 kt of phosphorus, 85 kt of potassium, and 8 Mt of CO_2 emission would have been implied. In this sense, it is fundamental to consider that the effect of sustainability initiatives (e.g., the gradual increase of the share of EU palm oil covered by the Roundtable on Sustainable Palm Oil certification – RSPO) might not immediately be captured due to the amortization criteria adopted for the temporal attribution of the CO_2 emission from land use change. While this might represent a limitation in terms of temporal sensitivity to changes in the production, it is necessary to think that cropland obtaining sustainability certification might derive from previously unsustainable practices such as, indeed, deforestation and peatland drainage, whose consequent emissions are not immediate. On the other hand, the new cropland generated through deforestation and peatland draining that was once exploited to satisfy EU chicken meat sector does not revert to its pristine state even if EU consumption of related crops decreases or ceases. Indeed, the global linked emission presents much more alarming trends (soybean and palm oil ED and EPD increased 36% globally over the analyzed period (Pendrill et al., 2020)) compared to the EU chicken meat sector (overall -48% for the same crops and period – Fig. 2). The guidelines recently released by the European Feed Manufacturers' Federation (FEFAC) might be helpful to address the future reduction of the environmental burden intensity of chicken feed to be consumed in the EU (FEFAC, 2021).

Mitigating actions should prioritize interventions on the three factors identified above. However, multiple constraints limit this possibility. For instance, while sustainable intensification within the EU is still possible (Godfray and Garnett, 2014), it could not prescind from resulting in larger environmental burden (Davis et al., 2016), especially in terms of impact on climate change (Mbow et al., 2017) and ecosystem services and biodiversity (Díaz et al., 2019). Furthermore, the forecasted reduced land availability (Castillo et al., 2018) and yields (Feyen et al., 2020; Kelly, 2019) indicate that, on one hand, further efficiency improvements at the cultivation phase might hardly reduce the environmental burden of future EU chicken meat production. On the other hand, imports of feed will still be required to cover a significant part of the chicken feed demand (European Commission, 2020). This contrasts the recent EU call for a deforestation-free communitarian trade (European Commission, 2021d), especially for soybean, and poses serious challenges to the EU Green Deal's climate neutrality target (European Commission, 2019b).

Our analysis indicates that the choice of trade partners is pivotal in shaping the environmental profile of the chicken diet and, in turn, of the chicken meat, due to the existence of remarkable trade-offs among different environmental aspects. This limits the potential benefits obtainable by changing trade partners, since a win-win solution is not always available, namely, a solution ensuring reduced environmental burden for all the environmental externalities considered.

Ultimately, further technical improvements at the rearing phase are unlikely due to physiological limits and animal welfare concerns (Siegel, 2014; Tixier-Boichard, 2020).

As discussed above, many constraints limit the overall effectiveness of a comprehensive mitigation through actions focusing on the current chicken feed composition. A possible alternative or complementary solution could be the substitution of some ingredients. However, the available substitution possibilities (El-Deek et al., 2020; Kebreab et al., 2016; Montha et al., 2021; Olkowski, 2018; Wang et al., 2021) present controversial results in terms of sustainability improvement (Smetana et al., 2019). Insect-based feed ingredients could represent a non-crop alternative (European Commission, 2019b) matching FTFS (European Commission, 2019c) with multiple beneficial aspects. If coupled with nutrient upcycling from waste (Bava et al., 2019) it could avoid cultivation impacts (Bosch et al., 2019) and valorize side streams (Fowles and Nansen, 2020). Nevertheless, a limitation is imposed by the current regulation which strongly obstacles the application of this solution (IPIFF, 2020).

Ultimately, solutions for lowering the intensities of food production chains will likely need to be coupled with actions and strategies on the consumers' side (Bruno et al., 2019). This will be necessary if the EU is to successfully ease a decarbonization and a shift towards more sustainable EU food systems (Galli et al., 2020; B. F. Kim et al., 2019; Willett et al., 2019). Furthermore, this would make EU diets healthier and possibly place a lower burden on the healthcare systems of EU Member States (Westhoek et al., 2021). However, to be successful, shifts in dietary patterns should be encouraged by means of incentives, inclusion of sustainability criteria in national dietary guidelines (Springmann et al., 2020), public policies, as well as regulatory changes. These should be flanked by actions to increase food and health literacy for citizens and governing bodies ultimately aimed at encouraging individuals to consume products with lower environmental burden and higher health and nutritional benefits (Laurent et al., 2022; Mongo et al., 2021; Westhoek et al., 2021). This assumes a particular relevance when replacing red meat with poultry meat (Clark et al., 2019; Poore and Nemecek, 2018; Resare Sahlin et al., 2020).

From an intensity viewpoint (unit of pressure or impact per kg of chicken meat – carcass weight), our results substantially match those in the existing literature (Tab. S10-S11), although no paper has provided such a wide range of multi-dimensional estimates so far. For example, in terms of land use, Leinonen et al. (2012) estimated that 5.8 m^2 are required to produce 1 kg of chicken meat carcass weight (CW), while Elferink and Nonhebel (2007) estimated a value of 5.9 for the same unit, which are in line with our results (5.6 m^2 /kg CW). Conversely, Wiedemann et al. (2017) found a land intensity of 14-22.5 m^2 /kg CW, which is significantly higher than our finding probably due to the very different diet, slaughter age, and FCR. The same study also assessed the blue water intensity, again finding higher results (95.5 dm^3/kg CW) compared to the present study (71.4 dm^3/kg CW), while Krauß et al., (2015) found a total water intensity – blue plus green water – (3.33 m^3/kg CW) higher than our results (2.5 m^3/kg CW), but possibly due to the inclusion of the parental flock in the calculation. Looking at the global warming potential, FAO (2013) indicated that on average (2004-2006) industrial broiler systems in Europe have a CO_2 emission from LUC intensity ranging from 0.2 to 2.6 kg CO_2/kg CW. Our estimates fall in this range (0.5 kg CO_2/kg CW). Wiedemann et al. (2017) estimated a higher value (1-1.2 kg CO_2/kg CW) but considered different temporal and geographic boundaries, including a different method for the estimation of emission from LULUC. No other study was found with scope, level of aggregation, and phase distinction matching our study, thus standing for a meaningful comparison.

While being the most comprehensive multi-dimensional environmental analysis of the feed for the EU chicken meat industry, our analysis presents some limitations. For instance, the use of nutrients from organic fertilizers (e.g., manure or sewage sludge) is not accounted for, limiting the possibility to fully capture the disruption of the normal nutrients cycles that derives from international trade such as the one required to support the EU chicken meat industry, where soil might get impoverished beyond EU borders while receiving overnutrition within. Furthermore, the depreciation (or amortization) time considered in the present analysis – 10 years – could represent a source of discrepancy with the results of other studies due to its arbitrariness. However, as discussed above, this issue cannot currently be solved, since no agreement has been reached among scholars. Furthermore, since the analysis relies on a vast and heterogeneous amount of data – entering the calculation at various stages – a robust sensitivity analysis could not be carried out. However, the most critical factors influencing the results in both intensive, extensive, and temporal terms are the FCR, the final weight of the chicken, together with feed sources.

Finally, applications of the results of this study can be extended to track the pathways of environmental burden if they are coupled with the flows of any country importing chicken meat or feed from the EU, thus revealing the footprint from a consumer perspective (Osei-Owusu et al., 2019). Similarly, the same approach applied in the present study could be applied to the egg industry. On the other hand, this study could support the development of further initiatives such as the FEFAC guidelines.

5. Conclusions

Our findings reveal the multiple and various factors that drive the environmental burden associated with the feed utilized by the EU chicken meat industry, providing insights into the many possibilities and constraints that will affect the environmental sustainability of the forecasted growth of the EU chicken meat industry. As feed accounts for a remarkable part of the overall environmental burden of meat production, our paper demonstrates the importance of focusing on feeds.

The analysis presented is in line with recent debates around the need for more informative analyses identifying the multifaceted environmental impact of food systems (Galli et al., 2022; Caro, 2023;

Sporchia et al., 2023). However, a silver-bullet solution for a sustainable EU broiler industry could not be identified and will hardly be possible in our opinion. Accordingly, policies should encompass multiple simultaneous actions, targeting both domestic production and international trade, and considering the trade-offs among multiple pressures and impacts. Moreover, considering the discussed limits of current policies and strategies, future EU interventions should consider supporting the utilization of existing feed substitutes or additives, which could help overcoming the challenges that a shift towards a sustainable and healthier circular food system entails, while reducing the feed-food competition. Since food systems alone account for about one third of the global anthropogenic impact on climate change, they should receive priority attention within political agendas (Crippa et al., 2021). Being the largest global food exporter and the third largest importer (European Commission, 2021c), by acting on the pivotal broiler sector the EU could proactively deliver on its ambition to lead the global sustainability transition (European Environment Agency, 2019).

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FS: Conceptualization; Data curation; Formal analysis; Investigation; Methodology, Writing - original draft; Visualization
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TK: Conceptualization; Writing - review & editing; Validation
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DC: Conceptualization; Investigation; Methodology; Writing - review & editing; Validation; Supervision

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract

Highlights

- We assess the environmental burden related to the EU chicken feed consumption.
- EU chicken meat industry causes environmental burden in foreign countries.
- The environmental footprint is not decoupled from production volumes.
- Sustainable intensification and revised trade pathways are key drivers.
- Future challenges require actions on multiple political ad technological aspects.