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Embodied HANPP of feed and animal products: Tracing pressure on ecosystems along trilateral livestock supply chains 1986–2013

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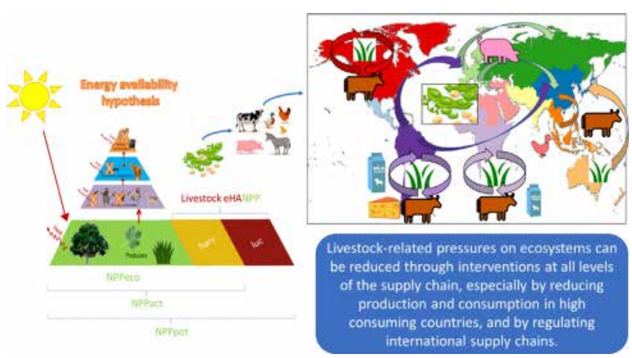
HIGHLIGHTS

- We trace HANPP embodied in trilateral supply chains of feed and animal products from 1986 to 2013.
- Livestock induced ~65 % of the global agriculture-related HANPP.
- eHANPP linked to interregional trade of feed increased from 4 to 6 % of livestock's eHANPP.
- eHANPP linked to interregional trade of animal products increased from 2 to 5 % of livestock's eHANPP.
- Livestock's ecological pressure can be reduced at all levels of the supply chain.

GRAPHICAL ABSTRACT



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ABSTRACT

The global livestock system puts increasing pressures on ecosystems. Studies analyzing the ecological impacts of livestock supply chains often explain this pressure by the increasing demand for animal products. Food regime theory proposes a more nuanced perspective: it explains livestock-related pressures on ecosystems by systemic changes along the supply chains of feed and animal products, notably the liberalization of agricultural trade. This study proposes a framework supporting empirical analyses of such claims by differentiating several steps of livestock supply chains. We reconstructed "trilateral" livestock supply chains linking feed production, livestock farming, and final consumption, based on the global flows of 161 feed and 13 animal products between 222 countries from 1986 to 2013. We used the embodied Human Appropriation of Net Primary Production (eHANPP) indicator to quantify pressures on ecosystems linked to these trilateral livestock supply chains. We find that livestock induced 65 % of agriculture's pressure on ecosystems, mostly through cattle grazing. Between 1986 and 2013, the fraction of livestock-related eHANPP that was traded internationally doubled from 7.1 % to 15.6 %. eHANPP related to the trade of feed was mostly linked to soybean imported for pig meat production, whereas eHANPP associated to traded animal products was mostly linked to cattle meat. eHANPP of traded animal products was lower but increased faster than eHANPP of feed trade. eHANPP was highest at the feed production level in South and North America, and at the consumption level in Eastern Asia. In Northern Asia and Eastern Europe, eHANPP was lowest at the animal products production level. In Western Europe,

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the eHANPP was equal at the animal products production and consumption levels. Our findings suggest that options to reduce livestock's pressures on ecosystems exist at all levels of the supply chain, especially by reducing the production and consumption in high-consuming countries and regulating international supply chains.

1. Introduction

Livestock is an important component of the global food system. Ruminants like cattle, goats and sheep transform non-edible biomass such as grass into products with indispensable nutrients for humans. Monogastric animals such as pigs and poultry recycle kitchen waste, and their excretions serve as organic fertilizers, which plays a key role in biogeochemical cycles (Galloway et al., 2003). In addition, livestock provides labor force in non-mechanized agricultural systems, often linked to ancient cultural heritage (Steinfeld et al., 2013), and supports the livelihood of more than a billion producers and retailers (FAO, 2009; Herrero et al., 2016).

However, livestock production induces considerable pressures on the environment (Herrero et al., 2015; Godfray et al., 2018), thereby contributing to the climate and ecological crises. Livestock is responsible for around 14.5 % of global GHG emissions (Gerber, 2013), uses 70 % of all agricultural land (arable land and grassland) (Van Zanten et al., 2018) and 58 % of total harvested biomass (Krausmann et al., 2008). Such burden is particularly due to the industrialization of livestock systems that resulted in high livestock densities in certain areas and a decoupling of feed and animal production, which jeopardized global nutrient cycles, causing nitrogen (N) and phosphorous (P) leakage and eventually eutrophication of surface waters (Lassaletta et al., 2016; Le Noë et al., 2017; Billen et al., 2021).

Livestock is a resource-inefficient way of feeding humanity due to the energy losses between trophic levels (Bonhommeau et al., 2013). For example, ~250 kg of feed biomass are required to produce one kilogram of protein from cattle meat (Herrero et al., 2015). Nevertheless, the global livestock system has grown rapidly since the mid-20th century, exceeding sustainable levels and health recommendations in various regions of the world (Willett et al., 2019). This excessive consumption of animal products has often been described as a consequence of consumer-driven dietary change, induced by raising income and urbanization (Steinfeld et al., 2013; Godfray et al., 2018). Yet, other approaches such as food regime theory have described the growth of the livestock sector as a consequence of the dominant paradigm since the 1940s, to grow and commodify agricultural production, and liberalize agricultural trade (Friedmann and McMichael, 1989; McMichael, 2009).

This paradigm has manifested into policies, such as the EU's common agricultural policy (CAP), which favored mass production, intensification, and commodification of animal products, while marketing campaigns from the livestock industry and governments contributed to making this increased production attractive to consumers (Gillespie and van den Bold, 2017; Godfray et al., 2018; Greenpeace, 2021). In the 1980s, structural adjustment policies, deregulation, and the large-scale adoption of biotechnology through large agribusinesses boosted the production and exports of soybeans in South America (Mempel and Corbera, 2021). Trade liberalization has also been described as an important driver of dietary changes, by increasing the availability and affordability of feed and animal products (Blouin et al., 2009; Thow, 2009; Thow and Hawkes, 2009; Kearney, 2010; Traill et al., 2014). For example, the GATT agreement on agriculture in 1995 and China's accession to the WTO in 2001 prompted access to cheap feed from South America, which, along with growing demand from a rising and urbanizing middle class, stimulated the further increase of Chinese and global meat production (Blancher and Rumbaugh, 2004; Pingali, 2007; McMichael, 2009; Lassaletta et al., 2016; Roux et al., 2021).

Food regime theory suggests that the growth of the livestock system and associated environmental pressures cannot be merely attributed to dietary choices by final consumers, but rather to geopolitical and economic strategies pursued at all stages of livestock supply chains. Yet, existing assessments of the ecological impacts embodied in global livestock supply chains provide limited information to support this theory, as they do not address the role played by intermediary stages of the supply chain, such as livestock production. Moreover, these studies establish a direct link between the locations of final consumption of animal products and the locations where land is used, and can, due to their design, not distinguish between the ecological impact associated with trade in feed and trade in animal products (Kastner et al., 2014; Pendrill et al., 2019; Uwizeye et al., 2020; Hoang and Kanemoto, 2021; Marques, 2021).

In this article, we introduce the concept of “trilateral” supply chains of feed and animal products to produce insights that can help to empirically test these tenets of food regime theory. We call supply chains “trilateral” because we distinguish trade flows between countries that (1) produce livestock feed, (2) produce animal products, and (3) consume these animal products. We developed a trilateral trade database, tracing the flows of 161 primary feed products and 13 primary animal products embodied in the global livestock supply chains between 222 countries from 1986 to 2013.

We quantified the ecological pressure of these trilateral livestock supply chains using the embodied Human Appropriation of Net Primary Production (eHANPP) indicator (Erb et al., 2009; Haberl et al., 2009, 2012; Kastner et al., 2015; Roux et al., 2021; Dorninger et al., 2021). Net Primary Production of vegetation (NPP) is the amount of organic material produced by plants through photosynthesis, net of the plant's own metabolic demands (plant respiration) (Haberl et al., 2014). It is the first trophic level of biomass production that provides energy to all heterotrophic species, i.e. all organisms that derive energy from ingesting organic materials (e.g. by feeding on plants or animals). Humans appropriate NPP by harvesting biomass (feed crops, crop residues, and roughage in the case of livestock) and by land-use change that alters the NPP of ecosystems. As humans appropriate more NPP, flows of trophic energy (e.g. food) available to other species are reduced, with consequences on biodiversity (Haberl et al., 2005; Cusens et al., 2012), the water cycle, the carbon balance of ecosystems, and other ecosystem functions (Haberl et al., 2014; Sutton et al., 2016; Zhang et al., 2021). The Human Appropriation of Net Primary Production (HANPP) offers a framework for quantifying the impact of land use on flows of NPP in ecosystems. The HANPP associated with global supply chains is called ‘embodied HANPP’, abbreviated as eHANPP (Erb et al., 2009). Previous eHANPP studies analyzed the role of bilateral agricultural trade on ecosystems at a product aggregated level (Kastner et al., 2015; Weinzettel et al., 2019; Dorninger et al., 2021; Roux et al., 2021). Mayer et al. (2021a) estimated the eHANPP of livestock production in the EU. However, no study has so far analyzed in depth the patterns of HANPP embodied in global supply chains of feed and animal products.

With our perspective of trilateral eHANPP flows, from feed production over livestock production to the consumption of animal products, we aim to answer the following questions:

1) How did the HANPP embodied in the global and regional consumption of specific feed and animal products evolve over the period 1986–2013?
2) How much HANPP was embodied in the products involved in different types of trilateral livestock supply chains?
3) How did international trade affect the HANPP embodied in the three stages of livestock supply chains in different regions?

We finally discuss implications for the governance of different types of livestock supply chains, arguing that a trilateral thinking illustrates how different actors along the supply chain play a role in stewarding a rapid and just reduction of the livestock system in countries with high production and consumption of animal products.

2. Methods

The calculation consists of (1) calculating crop and animal product-specific HANPP factors, (2) quantifying trilateral supply chains of feed and animal products, and (3) combining (1) and (2) to obtain the eHANPP in global feed and animal products supply chains, hereafter referred to as "livestock eHANPP" (Fig. 1). A detailed description of the method and download of the entire eHANPP data can be found in the attached Data in Brief article.

2.1. Product level HANPP factors

The HANPP framework consists of five components, NPP_{pot}, $HANPP_{luc}$, $HANPP_{harv}$, $NPP_{act,}$ and NPP_{eco} (Fig. 2). The NPP_{pot} is the net primary production of natural potential vegetation, i.e. the NPP of the vegetation that would prevail in the absence of any human land use under the current climate. Humans appropriate NPP by establishing a vegetation pattern that differs from potential vegetation, i.e. through land conversion and land use ($HANPP_{luc}$), for example when a forest is converted to cropland or pasture and used over the years, and by harvesting feed crops or letting livestock graze on pastures ($HANPP_{harv}$). The HANPP is the sum of the $HANPP_{luc}$ and $HANPP_{harv}$. The part of the vegetation growth left over to other species is called the NPP_{eco}. By construction, the higher the HANPP, the lower the NPP_{eco}, and the less energy will be available to other species. This may contribute to the extinction of some of these species along the trophic chain according to the energy availability hypothesis of biodiversity (Haberl et al., 2005; Haberl et al., 2007a, 2007b; Cusens et al., 2012). Furthermore, increasing the HANPP affects other ecosystem functions such as carbon storage, water availability, or wind erosion regulation (Haberl et al., 2014; Sutton et al., 2016; Zhang et al., 2021). The sum of the NPP_{eco} and $HANPP_{harv}$ is the NPP_{act}, the NPP of the vegetation actually observed on the land before the harvest.

HANPP and eHANPP had until now only been calculated at the level of aggregated products. We adjusted the calculation to disaggregate the HANPP and eHANPP to the highest possible product resolution, as explained in the linked Data in Brief article. Most of the required data were derived from the FAOSTAT database (Table S1). NPP_{pot} data were simulated with the LPJmL dynamic global vegetation model (Schaphoff et al., 2018), thereby using the CRU_TS4.03 historical climatology data from 1901 to 2018 (Harris et al., 2020).

2.2. Trilateral supply chains of feed and animal products

2.2.1. Bilateral trade and correction for reexports

The calculation of the bilateral trade data was mostly similar to the procedure described in (Kastner et al., 2011; Kastner et al., 2014; de Ruiter et al., 2017). This method assumes that domestic production and imports from all origins are proportionally redistributed to domestic consumption and exports. We built bilateral trade matrices between 222 countries for 283 traded vegetal feed products that we traced back to 159 primary crops. We considered 66 traded animal products that were traced back to 13 primary animal products. We corrected these for re-exports as explained in the Data in Brief article. This allowed us to derive the bilateral trade matrix $\overline{R}$ for any given crop, corrected for reexports, where $\overline{R}_{ij}$ is the apparent consumption of country *i* originating from country *j*. See Fig. 1 for an overview of all abbreviations given to matrices and vectors.

To calculate the matrices of animal product trade in feed crop equivalents $\overline{S}$, we multiplied the bilateral trade matrices of animal products by factors of feed product per ton of animal product (for all combinations of feed and animal products). These factors were calculated in step 1 using a

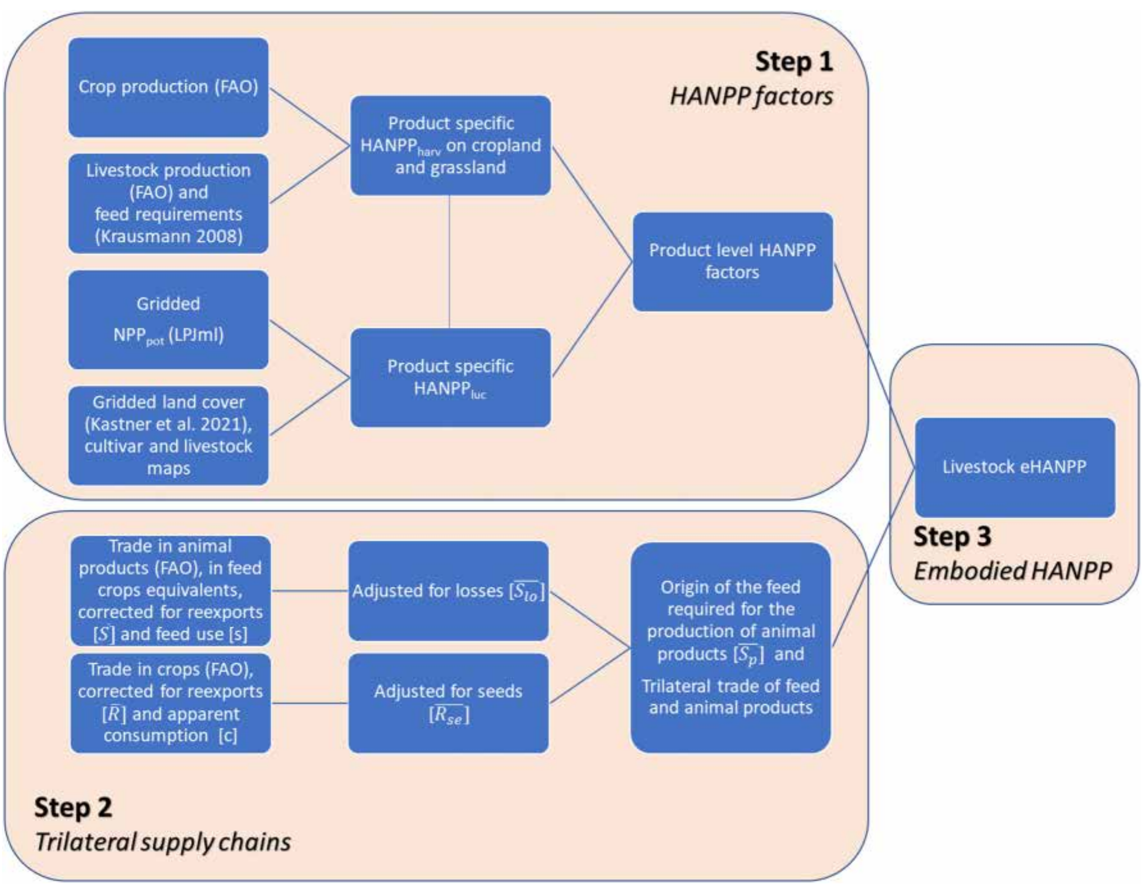

Fig. 1. Calculation steps. Data sources are referred to in round brackets (…). FAO data were downloaded with an API in July 2021. Matrix or vector names are written in square brackets […]. NPP_{pot}: potential Net Primary Production, $HANPP_{harv}$: HANPP induced by crop harvest or grazing, $HANPP_{luc}$: HANPP induced by land use change.

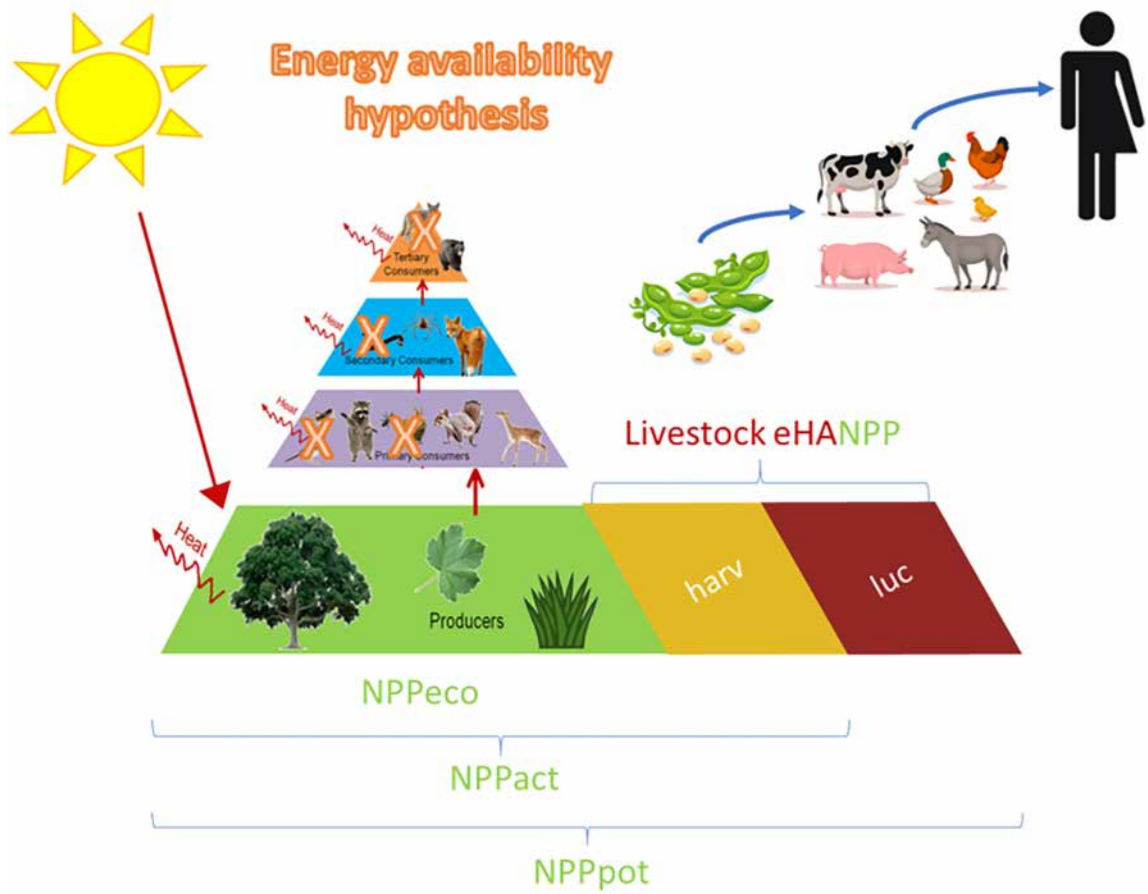

Fig. 2. The livestock eHANPP framework. harv = harvest, luc = land use change. Based on the observation that higher HANPP leaves less NPP to ecosystems (i.e., reduces NPP_{eco}), the energy-availability hypothesis claims that rising levels of HANPP are poised to reduce species richness and thereby biodiversity.

grazing gap method, i.e. by calculating grazed biomass as the residual feed requirement after subtracting market feed and crop residues used as feed, following Krausmann et al. (2008). Feed products reported in the FAO sometimes correspond to several primary crops (for example the category brans include brans from wheat, rice, barley, maize, etc.). Feed products were hence allocated to the primary products found in the corresponding FAOSTAT definition, proportionally to the apparent consumption of each crop (row sums of $\overline{R}$).

2.2.2. End uses and adjustments for seeds and losses

We proportionally allocated the trade data of crops to their end uses (feed, direct human food, and other uses), adjusting for seed use and losses, based on the commodity balances (CBS) from the FAO. Trade matrices are to be adjusted to seed use, as the consumption of a crop in a given country should include the quantity of seeds globally used to produce that crop, but exclude the amount of that crop that this country is using for its own seeds. We adjusted trade matrices for seed use, by adding seeds to the production (and exports), and eventually removing them from the consumption and imports (Eq. (1)). We call $\overline{R_{se}}$ the trade matrix adjusted for seeds.

$$\overline{R_{se}} = \left(1 - \frac{\text{seeds in consuming country}}{\text{consumption in consuming country (including seeds)}}\right) \times \overline{R} \times \left(1 + \frac{\text{seeds in producing country}}{\text{production in producing country}}\right) \quad (1)$$

We allocated losses to feed, food, and other uses, and adjusted the traded matrices for losses. We denote as $\overline{S_{lo}}$ the matrix of losses associated to any given animal product, in feed crops equivalent, adjusted for the losses in feed crops (Eq. (2)).

$$\overline{S_{lo}} = \overline{S} \times \left(1 + \frac{\text{losses}}{\Sigma_{\{\text{feed;food;other uses}\}} \textit{final uses}}\right)_{\textit{producing country}} \quad (2)$$

2.2.3. Trilateral trade between feed producers, animal product producers, and final consumers

We combined the trade matrices of bilateral crops and animal products to build the trilateral livestock supply-chain data, thereby differentiating feed production, livestock production, and the consumption of animal products. We started from the feed used to produce animal products in each country (e.g. how much soy is fed to pigs in Germany). In Eq. (3), we then quantified the mix of origins of each crop (e.g. which share of the soy consumed in Germany originates from Brazil). Combining the feed used and the mix of origins of crops gives the origin of crops used for feed in each country, called $\overline{S_p}$ in Eq. (4) (e.g. how much soy fed to pigs in Germany comes from Brazil). We then multiply each flow of feed crops with the mix of destinations of the animal product (e.g. which share of the pig meat produced in Germany is exported to China) in feed crops equivalents, to establish the trilateral supply chain (e.g. how much soy from Brazil is used in Germany to produce pig meat which is exported to China).

s is the vector of feed used to produce a given animal product, adjusted for losses (the column sum of $\overline{S_{lo}}$). c is the vector of apparent consumption of crops adjusted for seed use (the row sum of $\overline{R_{se}}$). Hereafter, a hat over a vector ($\widehat{c}$) represents the diagonal matrix with the entries of that vector (c).

$$\text{mix of origins} = \widehat{c}^{\,-1} \times \overline{R_{se}} \quad (3)$$

is the mix of origins for that crop adjusted for seed use.Then

$$\overline{S_p} = \widehat{s} \times \widehat{c}^{\,-1} \times \overline{R_{se}} \quad (4)$$

is the trade matrix reflecting the origin of the feed required for the production of that animal product. $\overline{S_{p_{ij}}}$ is the feed originating from country j used to produce an animal product in country i.

$$\text{mix of final destinations} = \overline{S_{lo}} \times \widehat{s}^{\,-1} \quad (5)$$

is the mix of final destinations of an animal product in each country's production of that animal product. By multiplying each entry of $\overline{S_p}$ by the mix of final destination of the animal product, we calculated the trilateral trade flows.

2.3. HANPP embodied in trade, production, and final consumption of feed and animal products

For eHANPP from cropland, we calculated the HANPP (and other HANPP components, such as $HANPP_{harv}$, $HANPP_{luc,}$ or physically cropped area) embodied in the trilateral trade of feed and animal products, by multiplying the HANPP factors calculated in step 1, with the corresponding trade matrices.

For eHANPP from grassland and crop residues used as feed, we applied the HANPP factors directly to the trade matrices of animal products. For simplicity, we omitted international trade in crop residues (straw) and roughage (grass and non-marketed fodder crops such as green maize) because these fractions are usually not transported over longer distances. The HANPP of grazing and crop residues was hence entirely attributed to the domestic production of animal products.

Asses, camels, horses, and mules are usually not meant to produce meat and milk, but rather to provide services (transport, work, or leisure), that are enjoyed domestically. As we could not quantify these services, we allocated all the eHANPP of these animals to domestic consumption, rather than allocating it to the animal products reported in the FAO (e.g. horse meat), to not overestimate the HANPP embodied in these products and international trade. Note that feed used for these animals can however be imported.

All calculations steps are performed at the country level, but will be only displayed at the world region level in this article (Fig. 3). The country level (trilateral) data can be downloaded under https://doi.org/10.5281/zenodo.6617859.

3. Results

3.1. HANPP embodied in global and regional consumption of feed and animal products

Livestock induced ~65 % of the global agriculture-related HANPP over the period; this fraction was slightly declining (Figs. 4b and S1). In the year 2013, 0.25 Gt dm/yr of animal products were consumed globally, requiring 8 Gt of feed and inducing 13.2 Gt dm/yr of HANPP. HANPP embodied in the global consumption of feed and animal products increased by 11 %, from 11.9 to 13.2 Gt dm/yr between 1986 and 2013 (Fig. 4b and d), for 0.25 Gt dm/yr of animal products consumed in 2013. This increase was rather due to the increase in harvest than in land use change (Fig. S6), i.e., intensification rather than expansion of cropland and grassland. Over the study period, 74 % of the HANPP embodied in animal feed was related to grazing, roughage as green maize, or crop residues used as feed. Note that the HANPP of crop residues only include the harvest, as residues were not allocated any HANPP from land use change. 26 % of the HANPP embodied in animal feed was related to market feed crops. HANPP embodied in global grazing increased from 8.1 to 8.3 Gt dm/yr between 1986 and 2013, with a spike at 8.8 Gt dm/yr in 2010. Despite the increase in market feed crops from 0.8 to 1.3 Gt dm/yr, the HANPP embodied in feed crops (excluding residues used for feed) slightly decreased over the period, from 3.50 to 3.36 Gt dm/yr, revealing important efficiency gains of animal feed crops production. The $HANPP_{harv}$ of feed crops even became higher than the potential NPP on cropland used to produce feed (Fig. S6).

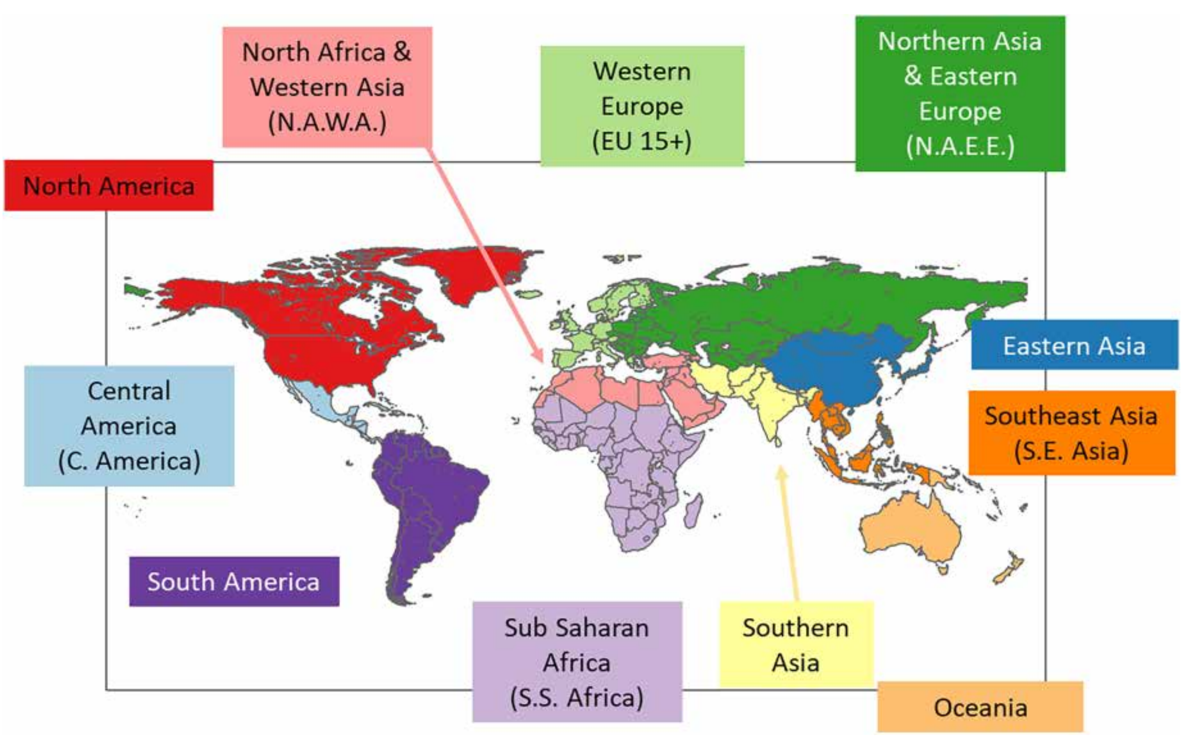

Fig. 3. World regions (abbreviations) used to present results in an aggregated manner.

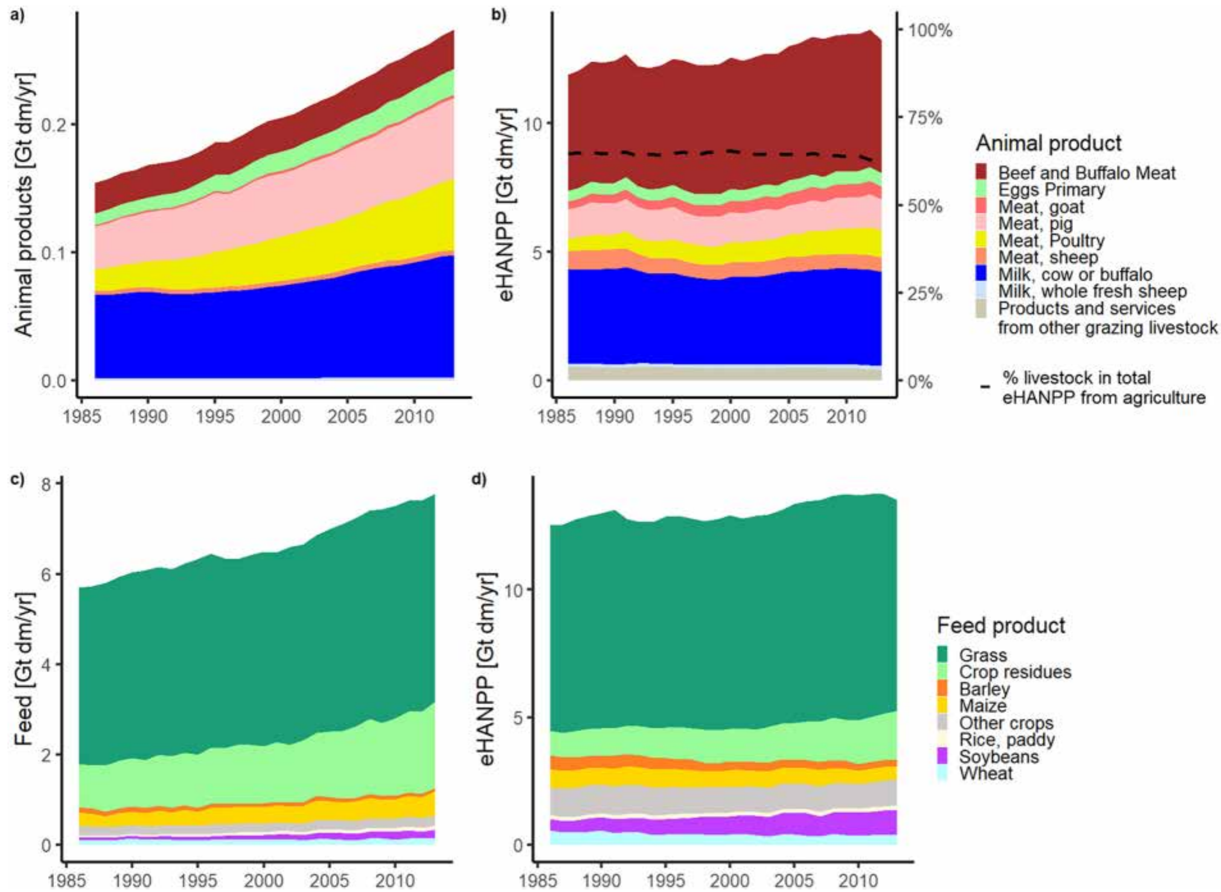

Fig. 4. Global consumption (a) and eHANPP (b) of animal products. The dashed line (right axis in b) represents HANPP associated with livestock in % of the total HANPP embodied in agricultural products (for feed, direct human food, materials, or energy). Global feed use (c) and eHANPP (d) of feed production.

HANPP embodied in soybeans used as feed increased, while HANPP embodied in other feed crops decreased over the period. HANPP embodied in maize used as feed was low compared to the amount of maize used as feed, while HANPP embodied in soybeans used as feed was disproportionally high, reflecting the differences in crop yield between the two crops and the fact that soybeans were largely grown in tropical regions, inducing substantial amounts of $HANPP_{luc}$.

Cattle-derived products were on average responsible for two-thirds (67 %) of the global livestock-related eHANPP (39 % for beef and buffalo meat, and 28 % for dairy products from cow and buffalo) (Fig. 4b). In comparison, 9.4 % of global livestock-related eHANPP were linked to pig meat, and 6.1 % to poultry meat. The increase in HANPP embodied in animal products was mainly associated with trends in beef and buffalo, poultry, and goat meat consumption, while eHANPP of pig meat was rather constant over the period due to important HANPP efficiency gains in feed production. The eHANPP of cow milk decreased.

HANPP embodied in the consumption of animal products increased in most regions (Fig. 5), especially in Eastern Asia (+0.57 Gt dm/yr), Sub-Saharan Africa (+0.41 Gt dm/yr), and South America (+0.41 Gt dm/yr). Livestock eHANPP was more or less constant in Western Europe (EU 15+) and Oceania and decreased substantially in Northern Asia & Eastern Europe (N.A.E.E.) after the fall of the Soviet bloc (−1.1 Gt dm/yr). In 2013, beef and buffalo meat had the highest eHANPP in all regions, except for Southern Asia and in North Africa & Western Asia (N.A.W.A.), where eHANPP was dominated by the consumption of dairy products from cows and buffalos. HANPP embodied in the consumption of pig meat was important in Eastern Asia, N.A.E.E., and Western Europe, but comparatively small in other regions. See Figs. S2–S4 for regional and per capita consumption compared to the "Lancet diet" (Willett et al., 2019), and eHANPP of feed and animal products. Livestock eHANPP was mostly due to harvest in temperate regions, while both harvest and land use change were important in tropical regions except in Southern Asia (Fig. S5).

3.2. HANPP embodied in trilateral livestock supply chains

The HANPP embodied in the final consumption of animal products is the result of a trilateral system of feed and animal products supply chains that link feed producers, animal product producers, and final consumers in two separate steps, i.e. the trade between (1) feed producers and animal product producers, and (2) animal product producers and final consumers (Fig. 6).

Fig. 6 reveals four categories of trilateral livestock supply chains, according to whether feed and animal products are supplied within world regions (domestic supply or intraregional trade) or traded across regions. Fig. 7 summarizes the shares of each category of trilateral supply chains in the global eHANPP of livestock for the period 2011–2013, and provides representative examples for each category. Overall, the global livestock system is typically dominated by fully domestic or intraregional livestock supply chains, which however decreased from 94 to 88 % of the global livestock-related eHANPP between 1986 and 2013. Domestic eHANPP was dominated by cattle meat and milk, mostly fed with grass. HANPP embodied in interregional feed trade grew from 4 to 6 % of the global livestock-related eHANPP, and was often linked to soybean exports, mostly used for the production of monogastric animals (pigs and poultry). HANPP embodied in interregional trade of animal products grew from 2 to 5 % of the global livestock-related eHANPP, and was linked mostly to cattle meat exports, fed with grass. The eHANPP of livestock supply chains with both interregional trade of feed and animal products (hereafter called spill-over) was marginal, and mainly involved soybeans exported from South America to Western Europe or Southeast Asia, used to produce and export

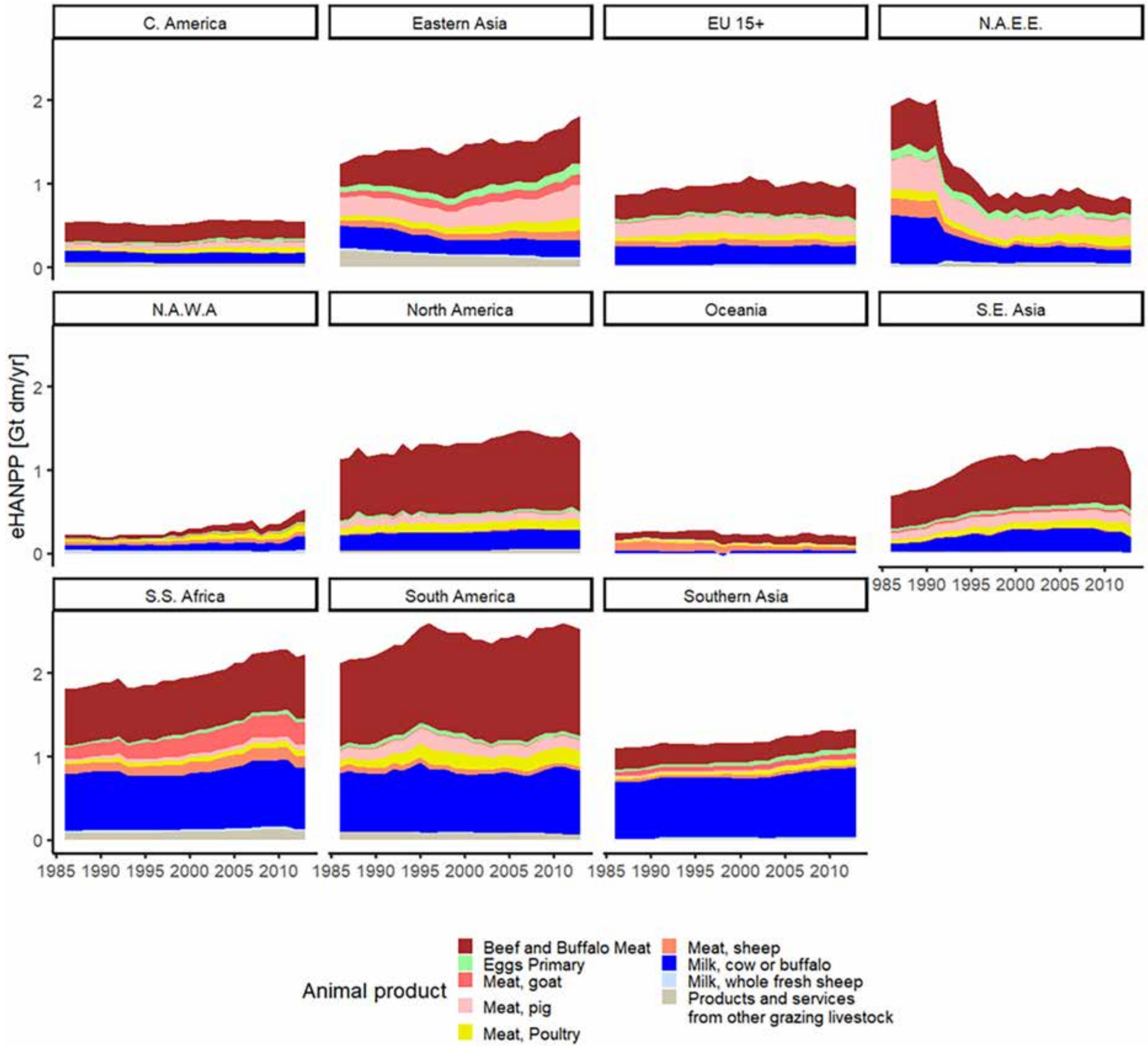

Fig. 5. HANPP embodied in the consumption of animal products by regions.

pig and poultry meat or dairy to N.A.E.E. and Eastern Asia. Note that the share of trade would be higher at the country level than at the world region level. Fig. S7 zooms further into interregional supply chains.

3.3. A typology of regional patterns

The share of feed crops traded internationally increased from 13 to 21 % over the period (grazing and roughage were assumed to be only domestic). Most notably, the share of soybeans used as feed traded internationally was already 48 % in 1986 and rose to 58 % in 2013. Between 1986 and 2013, the share of international trade in animal products rose gradually from 4 to 10 % of global consumption, especially for beef, pig meat, and dairy. The share of poultry meat traded internationally first rose with similar yearly rates but stabilized at 10 % since the early 2000s. International trade of sheep meat was already at 10 % in 1986 and stayed almost constant over the period. Consequently, the share of the total global livestock eHANPP that was traded internationally (as feed or animal products) more than doubled, from 7.1 % to 15.6 % over the period.

International trade of feed and animal products determines in each region whether the eHANPP of livestock is more important at the feed producer, the animal product producer, or the final consumer level (Fig. 6). We classified the world regions according to their role in the global trade of feed and animal products and their importance at each level of the global trilateral livestock system (Fig. 8).

3.3.1. Absolute exporters

We identified South America, North America, and Oceania as absolute exporting regions of feed and animal products, both in terms of eHANPP and biomass (Figs. 8 and S8). In absolute exporting regions, eHANPP was higher at the feed and animal product producing level than at the consumption level (bars get consecutively smaller from left to right in Fig. 6). For example, on average between 2011 and 2013, South America held 24 % of the global livestock eHANPP at the feed production level, 21 % at the animal product production level, and 19 % at the final consumption level. South America was the highest exporter of livestock eHANPP (627 Mt. dm/year), experiencing a 3.5-fold increase in livestock eHANPP exports since 1986, reaching 22 % of its HANPP embodied in feed production in 2013. Interregional livestock eHANPP exports from South America were mostly linked to soybeans exports (used to feed pigs and poultry in importing regions) but also increasingly to beef and poultry meat exports.

North America was the largest livestock eHANPP exporting region in 1986. Its livestock eHANPP exports increased at a slower rate than those from South America, from 219 Mt. dm/yr in 1986 to 324 Mt. dm/yr in 2013. In 2013, 20 % of North America's HANPP embodied in feed production was exported to other regions. Interregional livestock eHANPP exports from North America were mostly linked to exports of soybeans, beef and maize. However, North America as well imported a large amount of HANPP embodied in cattle meat from Oceania.

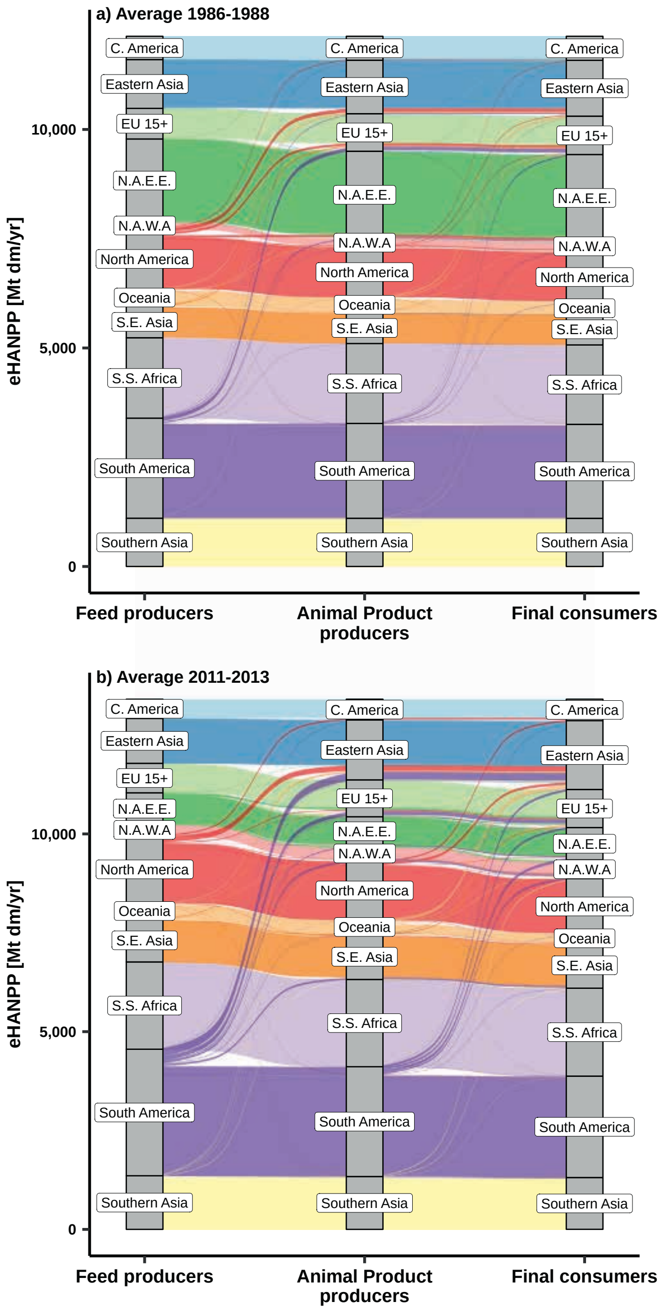

Fig. 6. Trilateral livestock eHANPP flows between the regions producing feed, producing animal products, and consuming animal products. A) average 1986–1988, b) average 2011–2013. We displayed only flows of more than 1 Mt. dm/yr of eHANPP, thereby covering 99.6 % of the data. Flows on the left-hand side, between the feed producer and the animal product producer columns, correspond to HANPP embodied in trade and domestic use of feed. Flows on the right-hand side, between the animal product producer and the final consumer columns, correspond to HANPP embodied in trade and domestic consumption of animal products. Colors correspond to the initial origin of the supply chain (feed producing region). For visualization reasons, flows moving down are more transparent than flows moving up the figure.

Interregional livestock eHANPP exports from Oceania slightly increased over the period from 152 Mt. dm/yr to 196 Mt. dm/yr. In 2013, 51 % of Oceania's HANPP embodied in feed production was exported to other regions. These were mostly linked to exports of beef, and to a lesser extent sheep meat and dairy. Oceania was however exporting relatively little feed.

Although South America was the largest livestock eHANPP exporter, North America and Oceania (and Western Europe) exported more animal products than South America in terms of biomass (Fig. S8).

3.3.2. Absolute importers

In contrast, in absolute exporting regions, eHANPP was higher at the consumption level than at the animal product and feed producing levels (bars get consecutively higher from left to right in Fig. 6). For example, on average between 2011 and 2013, Eastern Asia held 8 % of the global livestock eHANPP at the feed production level, 11 % at the animal product production level, and 13 % at the final consumption level. We categorized Eastern Asia, North Africa & Western Asia, Central America, and Southeast Asia as absolute importers. Eastern Asia's livestock eHANPP imports increased rapidly between 1986 and 2013, from 152 to 604 Mt. dm/yr. Eastern Asia's eHANPP imports were driven by soybean imports (serving pig meat production) and to a lesser extent cattle meat imports. In terms of biomass, maize was replaced by soybeans as the most imported feed crop in Eastern Asia. Between 2011 and 2013, 22 % of the HANPP embodied in Eastern Asia's consumption of animal products were linked to interregional imports of feed crops; 12 % to imports of animal products, and 0.7 % were causing interregional spillovers beyond the region from whom Eastern Asia was importing its animal products (Figs. 6 and S7).

eHANPP related to interregional feed and animal products imports of North Africa & Western Asia (N.A.W.A.) started increasing in 1997 and reached 237 Mt. dm/yr in 2013. In 2013, 43 % of N.A.W.A.'s HANPP embodied in consumption originated from other regions. These eHANPP imports were mostly linked to imports of cattle meat, soybeans, and barley. Between 2011 and 2013, N.A.W.A's eHANPP imports were dominated by imports of animal products from South America, and imports of feed from South America or N.A.E.E.

Interregional livestock eHANPP imports of Central America increased until 2002 and slightly decreased afterward. Between 2011 and 2013, Central America's livestock eHANPP imports were equally distributed among feed and animal products imports from North America.

eHANPP related to interregional imports of feed and animal products of Southeast Asia increased steadily over the period and were mostly linked to soybeans imports (often used for poultry meat) and to a lesser extent cattle meat and dairy imports. Between 2011 and 2013, eHANPP related to Southeast Asian imports were mostly linked to feed imports from South and North America, and animal products imports from Oceania.

3.3.3. The Western European paradox

Western Europe's livestock-related eHANPP was highest at the final consumption level (7.2 % of the global livestock eHANPP), but its share at the animal product production level was almost similar (7 %), compared to its 5.6 % at the feed producer level. This was due to the region's seemingly paradoxical situation of being both the second largest importer of livestock eHANPP, but also the second largest exporter of animal products in terms of biomass (Fig. S8). We found four key aspects of this paradox. (1) Western Europe imported high amounts of feed and beef from HANPP-intensive regions such as South America and N.A.E.E. (2) Western Europe exported mostly pig meat, dairy, and poultry meat rather than beef, which contributes more in terms of biomass than eHANPP. (3) Western Europe had a low NPP_{pot} and relatively efficient production of livestock, leading to comparatively lower eHANPP per ton of domestically produced product. (4) A large share of the feed used to produce the exported pig and poultry meat was originating from other regions, hence not affecting the HANPP domestically.

Interregional livestock eHANPP imports in Western Europe started increasing in 1990 and were overall rather constant afterward at ca. 350 Mt. dm/yr. 31 % of Western Europe's HANPP embodied in consumption in 2013 originated from other regions. These eHANPP imports were dominated by imports of soybeans, while HANPP embodied in beef imports grew around the year 2000. Western Europe's imports were inducing pressure on ecosystems in South America, and to a lesser extent, in Northern Asia & Eastern Europe, linked to the imports of both feed products and final

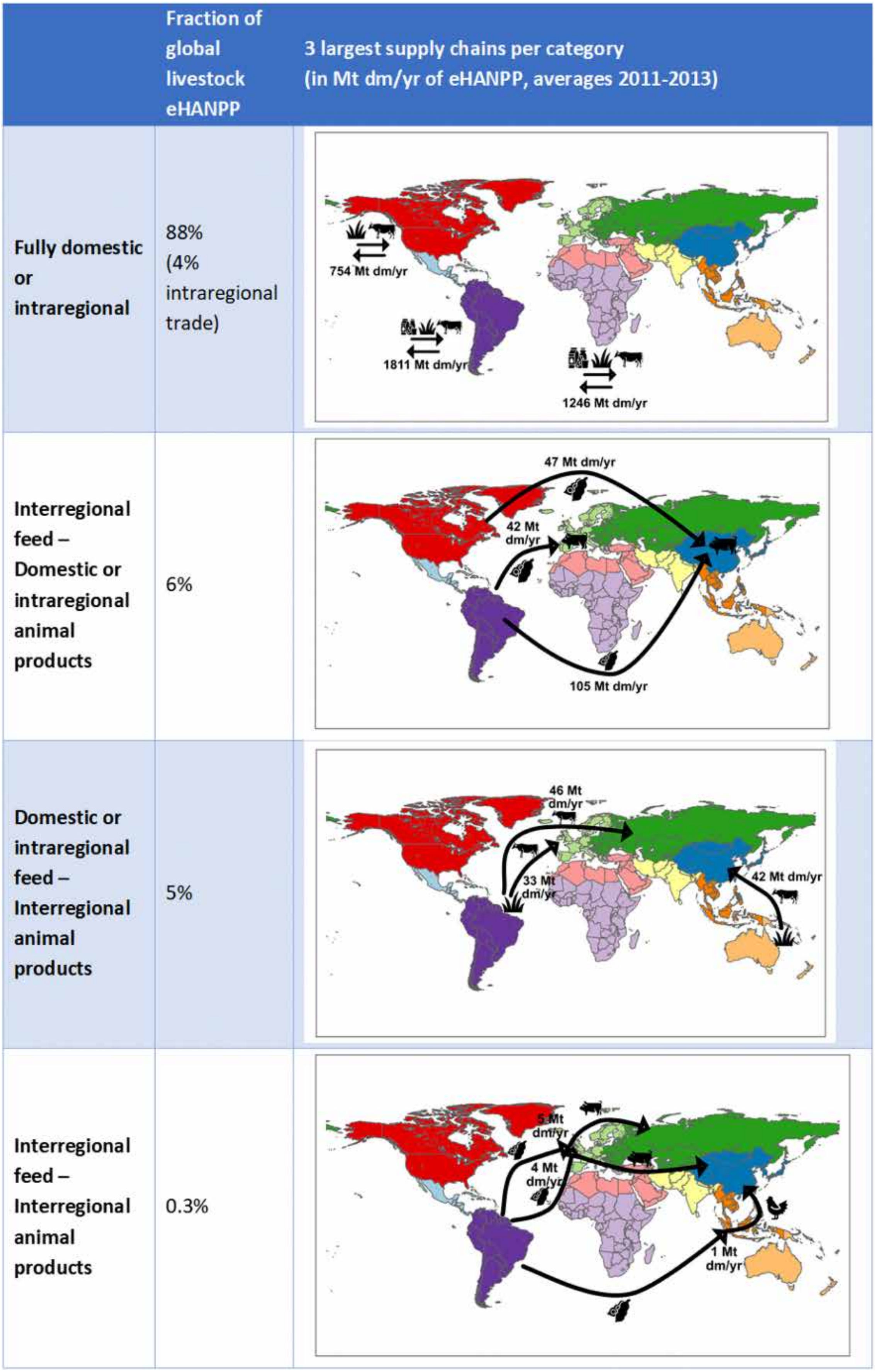

Fig. 7. Largest trilateral supply chains (in terms of eHANPP) by categories.

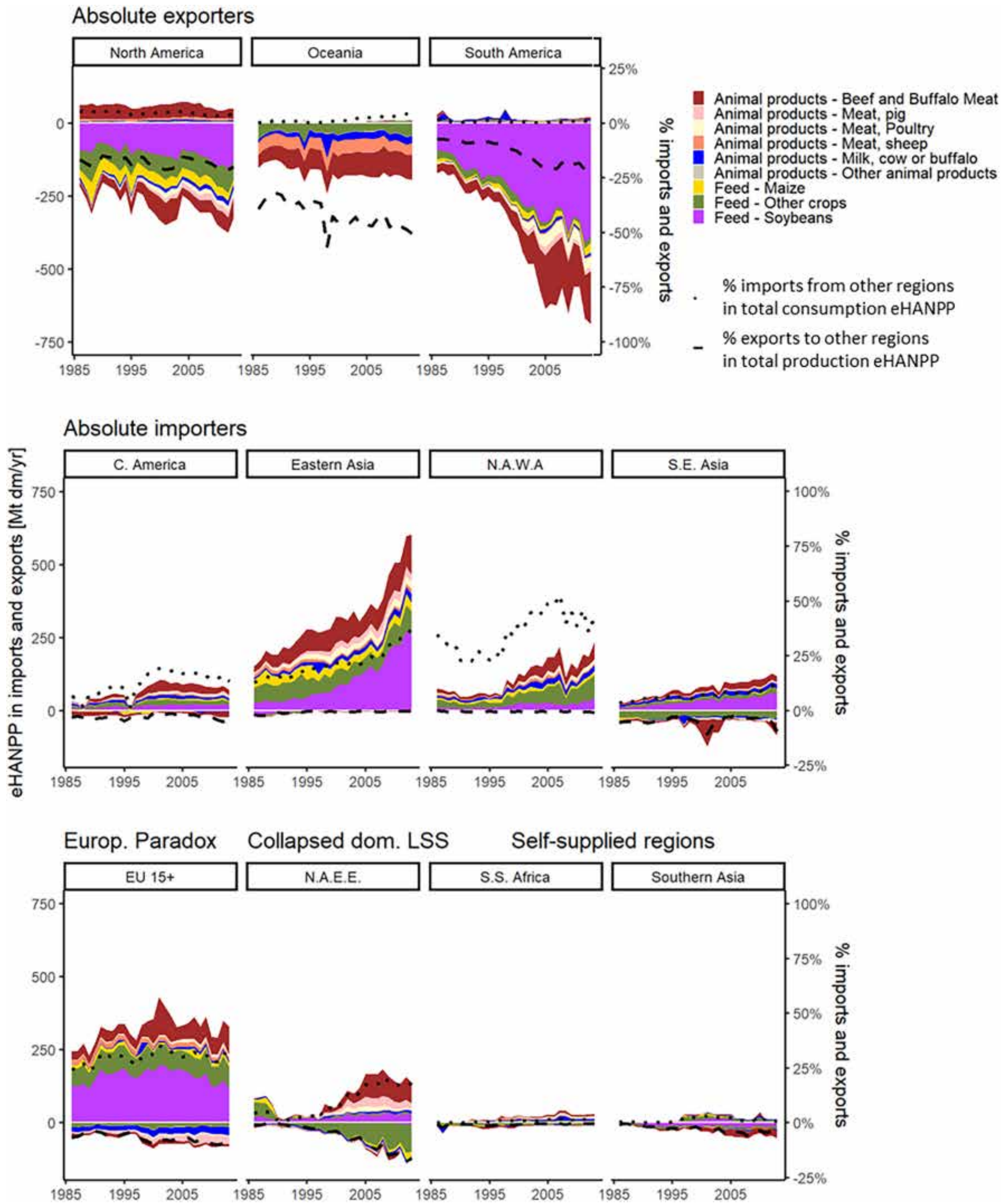

Fig. 8. HANPP embodied in imports (+) and exports (−) of feed and animal products. In the area graphs, in the (rare) cases when the feed used to produce the exported animal product is itself imported (spillover supply chains), the HANPP embodied in exports of animal products originates from another region. In such a case, the eHANPP is counted both in the feed export (import) of the region exporting (importing) the feed and in the animal product export (import) in the region exporting (importing) the animal product. In the dotted percentages lines, the eHANPP linked to spillover supply chains is attributed to the country producing the feed for the share of exports, and to the country consuming the animal product for the share of imports (i.e. they are not included in the shares of the "processing and reexporting" region). LSS: Livestock system.

animal products (Figs. 6 and S7). Livestock eHANPP imports from North America were entirely linked to feed imports, while eHANPP imports from Oceania and Southeast Asia were driven by imports of animal products.

Meanwhile, in terms of biomass, Western Europe's exports of animal products increased rapidly from the late 1990s, especially through pig meat exports to Eastern Asia and N.A.E.E., and through dairy exports to N.A.E.E. and N.A.W.A.

3.3.4. The collapsed domestic livestock system of N.A.E.E.

As its domestic livestock system collapsed after the fall of the Soviet bloc, Northern Asia and Eastern Europe became a net importer of cattle and pig meat (both in terms of biomass and eHANPP) and a relatively important exporter of feed. N.A.E.E. was hence the only region where eHANPP was lowest at the animal product production level compared to the two other levels. Interregional livestock eHANPP imports of N.A.E.E. dropped with the fall of the Soviet Union, through the drop of feed imports from North America. Interregional livestock eHANPP imports of N.A.E.E. increased suddenly between 1997 and 2005, mostly through cattle meat (and to a lesser extent soybeans) imports from South America, and stagnated afterward, at ca. 140 Mt. dm/yr. N.A.E.E.'s imports of livestock eHANPP were as well to a lesser extent linked to imports of pig meat from Western Europe. Interregional livestock eHANPP exports from N.A.E.E. gradually increased over the period from 18 Mt. dm/yr to 145 Mt. dm/yr (with a faster increase after 2000). Most of N.A.E.E.'s exports of livestock eHANPP were due to gradually increasing exports of sunflower seed, barley, and wheat, serving as feed mainly for pig and poultry meat consumed in N.A.W.A and Western Europe.

3.3.5. Largely self-supplied regions

The large regions of Southern Asia and Sub Saharan Africa had modest imports and exports of either feed and animal products. There were marginal increases in S.S. Africa's imports of poultry meat from South America and Western Europe or dairy from Western Europe, but these estimates remained comparably minor compared to other regions.

4. Discussion

4.1. Implications of the trilateral eHANPP approach for the governance of livestock supply chains

The eHANPP approach is a useful complement to other indicators of livestock's pressures on land. eHANPP enriches area-based estimates (Kastner et al., 2014) because it considers not only the amount of land area used, but also the land's fertility, and the intensity with which it is used (Schaffartzik et al., 2015). It complements embodied deforestation assessments (Pendrill et al., 2019; Hoang and Kanemoto, 2021) by quantifying not only the forest conversion resulting from livestock rearing, but depicts pressures on all terrestrial ecosystems. Finally, eHANPP not only considers current land use change but also the legacies of land converted in the past and still used nowadays (Bhan et al., 2021). However, the eHANPP indicator does not reflect various other ecological issues related to livestock, for example, the disruption of the nitrogen and phosphorus cycles through the disconnection of feed and livestock systems (Lassaletta et al., 2014; Billen et al., 2021). Nevertheless, the eHANPP approach provides useful insights in assessments of the ecological impact of telecouplings related to agricultural supply chains (Roux et al., 2021) and thereby supports the formulation of commodity-based governance (Gale and Haward, 2011; Sikor et al., 2013).

Disaggregating the HANPP and eHANPP data to the product level enabled us to zoom into the intricacies of feed and livestock supply chains. A large fraction of global agricultural biomass is used for feeding livestock, which is therefore associated with major pressures on biodiversity and ecosystem functions (Machovina et al., 2015). We showed that between 1986 and 2013, global feed use increased from 5.7 Gt dm/yr in 1986 to 7.8 Gt dm/yr in 2013, generating almost two-thirds of agriculture's pressure on ecosystems. These results are in line with other studies. Previous studies using the same methodology to estimate feed requirements found that in 2000, 6.5 to 7 Gt dm/yr of biomass were used to feed livestock, corresponding to 58 % of the global biomass harvest (Haberl et al., 2007a, 2007b; Krausmann et al., 2008). Wirsenius (2000), using a similar methodology, obtained only an 8 % lower feed use than the present study (5.6 Gt dm/yr between 1992 and 1994), which may be due to diverging disaggregation of production systems and the inclusion of more livestock species in our study. However, Bouwman et al. (2005) and Herrero et al. (2013) respectively found a 37 % and 38 % lower feed use than the present study. Our values for HANPP on grassland were in line with previous HANPP assessments (Haberl et al., 2007a, 2007b; Krausmann et al., 2013; Roux et al., 2021). However, the HANPP embodied in feed crops cannot be compared to previous studies, as it was isolated from other uses for the first time in this study. Nevertheless, the aim of this study was not to change the aggregate HANPP estimates but to provide a finer resolution of the results.

Except right after the fall of the Soviet Union and the region's important reduction in livestock production and consumption (Schierhorn et al., 2019), livestock's global pressure on ecosystems increased over the period. Despite important efficiency gains, especially in the production of feed crops, humans still appropriated on average 53 t dm/yr of net primary production to produce one ton of animal products in 2013, which underlines the inefficiency of using biomass for livestock. Given the emergency of the current biodiversity crisis (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019), further efforts to reduce the impact of livestock on ecosystems are commendable.

Our results show that policies focusing on reducing the ecological impact of cattle would yield the highest benefits for ecosystems, reiterating the call of previous studies (Machovina and Feeley, 2014; Machovina et al., 2015). The combined impact of cattle meat and milk encompassed two-thirds of livestock's pressure on ecosystems, mostly through grazing. Especially cattle meat showed a disproportionally large pressures on ecosystems, for a relatively small volume of meat supply, and per extension few nutritional benefits. In areas where cropping or vegetation regrowth is possible, cattle grazing hence represents an important waste of land resources, which could be used either to extensify vegetal food production, which can have important ecological benefits (Seufert and Ramankutty, 2017) or for the restoration of natural ecosystems. However, in areas where no other land use is possible, cattle production can have important benefits for food security, compared to monogastric species (pigs, poultry), which compete for the same crops that can be directly used as human food (Erb et al., 2012; Machovina et al., 2015).

The ecological impact of global livestock is embedded in a system of trilateral supply chains between feed producers, animal product producers, and consumers. Our results showed that around 2012, 84 % of livestock's pressure on ecosystems were linked to fully domestic supply chains, and another 4 % were fully within our defined continental world regions. This partly mirrors the results of other studies which found that the nitrogen or deforestation footprint of livestock was to a large extent domestic in most regions (Pendrill et al., 2019; Uwizeye et al., 2020). Nevertheless, the eHANPP indicator puts more emphasis on domestic production and consumption than studies of embodied deforestation (Pendrill et al., 2019; Hoang and Kanemoto, 2021). Even in largely importing regions such as Europe or Eastern Asia, most of the HANPP embodied in livestock consumption remains domestic, while embodied deforestation studies find that almost all deforestation embodied in the consumption of Western European countries such as France or Germany is imported. This difference is because indicators such as the HANPP, taking the potential of ecosystems as a benchmark (potential NPP, potential carbon stocks, etc.) put more weight on historical land use change, reflecting the idea that even in regions with little ongoing land use change, such as Western Europe, the production of animal products still affects ecosystems domestically, by preventing natural vegetation from regrowing, on land that may have been converted long ago (Bhan et al., 2021).

Regulating fully domestic supply chains might have no direct consequence on foreign ecosystems, but may affect them indirectly. For example, reducing feed or animal product production without harnessing consumption and imports would generate more imports and increase the pressure on foreign ecosystems. Reversely, reducing consumption without reducing the production and exports of feed and animal products may lead to further exports to other countries, hampering the decrease in domestic ecological impacts. This shows the importance of governing livestock production at all stages of the supply chain, including imports and exports.

At the end of the study period, 16 % of the pressure on ecosystems was embodied in international supply chains (12 % even across world regions), representing more than half of the overall HANPP embodied in all agricultural trade (Roux et al., 2021). Our trilateral approach could, to our knowledge for the first time, distinguish between eHANPP embodied in trade in feed and trade animal products. We saw that the pressure on ecosystems linked to trade in animal products was lower but increased faster than the pressure on ecosystems linked to trade in feed. At the end of the period, the pressures on ecosystems linked to feed and animal product trade were about equal at the global level, but differed strongly between regions. Moreover, the pressure on ecosystems linked to the international trade of feed was mostly linked to the production and consumption of pig and poultry products, while the pressure on ecosystems linked to the trade in animal products was mostly linked to cattle meat. The volume of trade in feed and animal products is expected to keep on growing, although at a slower pace than currently, mostly due to the stabilization of pig meat consumption and imports (FAO, 2021). However, trade agreements have kept on promoting further trade in feed and animal products. Notably, the EU-Mercosur agreement offered an increase of the EU quota of 99,000 tons of beef exports from Mercosur countries (Kehoe et al., 2020). Models have forecasted that the transfer of cattle production towards South America would be the most detrimental evolution of agricultural trade liberalization for land use and the climate (Verburg et al., 2009). The governance of international supply chains over the past decades has been mostly focused on voluntary standards and certifications, or company pledges such as zero deforestation commitments (Ingram et al., 2020). Despite noticeable improvements, voluntary measures have often fallen short in eliminating major threats to ecosystems from agricultural supply chains (Garrett et al., 2019; Ermgassen et al., 2020a, 2020b). This gave rise to calls for more stringent regulation, such as mandatory standards and due diligence (Bager et al., 2021; Schilling-Vacaflor and Lenschow, 2021), and for rethinking the role of trade agreements in governing land use change (Kehoe et al., 2020).

The last type of livestock supply chains we identified involved both trade in feed and in animal products. Such supply chains present an additional governance challenge as they may induce spillovers beyond the countries involved in solely one part of the supply chain (Liu et al., 2018; Meyfroidt et al., 2020). However, such supply chains only represented a very small share of livestock's global pressure on ecosystems. This phenomenon was noticeable primarily for specific supply chains, especially exports of pig meat from Western Europe to Northern Asia and Eastern European countries, and to Eastern Asia, which greatly relied on imports of Soybeans from South America. These spillovers can generate governance loopholes if not adequately addressed in bilateral trade agreements between the countries producing and those consuming animal products. For example, in the economic partnership agreement between the EU and Japan which entered into force in 2019, the parties reduced tariffs on meat and dairy exports from the EU to Japan, resulting in a 12.6 % increase in pig meat exports after the first year of the agreement (#EUTrade news, 2020). We hereby show that despite being praised for its sustainability components (Kettunen and Alvstam, 2020) this agreement may induce spillovers to ecosystems in countries supplying feed to the EU, notably South America. The EU has acknowledged this matter in the recent proposal for a regulation from the European Commission on deforestation-free products, suggesting to “cover both goods released for free circulation or exported from the Union market” (Proposal for a regulation on deforestation-free products, 2021). Nevertheless, even in Western Europe, these spillovers did not represent a large share of the total eHANPP of livestock.

4.2. From consumer-driven to supply-chain oriented narratives on dietary change

We understand the evolution from place-based and consumption-based accounting to the trilateral trade approach as a timid but important step to empirically illustrate a change towards a supply-chain narrative on dietary change. This narrative suggests that the pressure on ecosystems linked to livestock supply chains has not only been driven by feed producers or final consumers, but by decisions at all stages of the supply chain. Notably, livestock supply chains can be governed either at the feed producer, animal product producer, or final consumer level. We saw that exporting regions such as South America, North America, or Oceania can realize a higher global alleviation of ecological impacts by governing their production and exports of feed and animal products. Importing regions such as Eastern Asia and the Middle East can realize higher global impacts by governing their consumption and imports of feed and animal products. Regions whose international footprint is dominated by feed imports as Eastern Asia and Western Europe can additionally reduce their ecological impacts by governing the production of animal products. Western Europe can achieve similar reductions in ecological impacts by governing its production and consumption of animal products.

Reducing the ecological impacts of feed production ranges from reducing land cover change for feed crops and pasture, through sustainable intensification practices and the conservation of natural ecosystems, to agroecological practices on existing agricultural land, by increasing the NPP remaining in ecosystems after harvest, for example through permanent culture and improved grazing management (Gerber, 2013; Poux and Aubert, 2018; Mayer et al., 2021b). Reducing the pressure on ecosystems at the livestock production level is less often considered, and often simplified to livestock efficiency gains through farming practices such as the optimization of feed composition, selective breeding, or more controversial technologies such as growth promoters, metabolic modifiers, anabolic agents, and transgenic animals (Elferink and Nonhebel, 2007; Salter, 2017).

However, the potential of technologies and farming practices to reduce the ecological impacts of livestock is limited (Creutzig et al., 2016). Animal products, even produced with the best existing practices, still generate higher ecological impacts than plant-based food, for the same nutritional values (Poore and Nemecek, 2018). Technologies and farming practices are also not sufficient to achieve the 1.5 °C climate target (Clark et al., 2020). Compliance with ambitious climate targets hence requires the reduction of livestock in over-producing and over-consuming countries (Fig. S3) (Gillespie and van den Bold, 2017). Technologies and farming practices are not only insufficient to achieve ecological targets, but their potential is also far below the ecological benefits of reducing livestock (Herrero et al., 2016; Poore and Nemecek, 2018; Theurl et al., 2020).

The reduction of livestock is often reduced to the role of consumers, through voluntary or incentivized dietary change (Elferink and Nonhebel, 2007; Wellesley et al., 2015; Salter, 2017; Poore and Nemecek, 2018). Consequently, policies aiming to reduce livestock have “too often […] remain[ed] on the bottom ‘soft’ rungs of the policy ladder” (Willett et al., 2019) as education campaigns, labeling, or nudging (Springmann et al., 2018; Reisch and Sunstein, 2021).

Although we acknowledge the importance of consumers' dietary practices (Biermann and Rau, 2020) we see two major limitations of the consumer-driven narrative. First, it is questionable whether voluntary or nudged consumer-led changes can act fast enough to counteract the climatic and biodiversity crises in the absence of a deeper restructuration of livestock supply chains (Willett et al., 2019; Nature, 2021). Past changes in dietary habits as in post-war Europe and America were indeed never spontaneous (Dixon, 2009), but rather fostered by a set of governmental, institutional, and economic incentives, especially agricultural intensification policies, research programs, the voluntarist actions of corporatist farmer unions and tariff removals, aiming to increase the production and sales of animal products (Servolin, 1985; Dixon, 2009; Bureau and Thoyer, 2014). In the year 2012, OECD countries paid $52 billion as subsidies to support the production of fodder and animal products (Stoll-Kleemann and O'Riordan, 2015). Meanwhile, the marketing of meat and animal products, and corporate lobbying prevent effective campaigns aiming at changing people's eating habits (Gillespie and van den Bold, 2017; Godfray et al., 2018; Greenpeace, 2021). Therefore, as past shifts in dietary habits were not spontaneous, one may doubt that future shifts will be. Second, scientists, NGOs, and politicians often favor the consumer-driven narrative, because it does not target any economic actor in particular or their own responsibility to drive the change. However, the consumer-driven narrative implicitly assumes that changes in consumer demand shall trickle down to the producer, reducing the production of animal products through tougher competition, and therefore inducing the eviction of less competitive, likely small-scale or less industrialized farmers (Sheng et al., 2017).

The trilateral supply chain approach is an empirical application of an alternative narrative, beyond the dichotomy between farmers determining solely efficiency and consumers choosing the quantity of animal products, towards understanding diets as the consequence of decisions at all stages of the supply chain. It reflects the idea that any level of a supply chain is systemically linked to all other levels, domestically and through international trade. The final consumption of animal products can hence be reduced by cutting both the production and imports of animal products. Karlsson et al. (2021) for example argue how changes in feed trade may favor European consumption of ruminants over pigs and poultry. Mapes et al. (2022) found that future changes in international trade may have ambivalent results on diets.

The idea of influencing diets through interventions all along the supply chains of products is also reflected by strategy number two from Willett et al. (2019), suggesting not only better but also less animal production, through "incentives for primary producers to produce nutritious and plant-focused foods". The idea has as well timidly shown up in campaigns from civil society organizations (https://www.eating-better.org/betterbyhalf#0-3), and in policy proposals. After Dutch activist movements sued their government for not achieving its climate goals, the Netherlands became to our knowledge the first country to introduce a policy proposal to reduce the ecological impacts of the livestock sector by cutting livestock production by 30% (van Grinsven et al., 2019; Watts, 2020; Boztas, 2021). This measure has been estimated to yield considerable benefits for greenhouse gas emissions, nitrogen leakage, and biodiversity (Tiktak et al., 2021).

Instead of disguising the goal of reducing production behind a consumer narrative, the trilateral supply chain approach acknowledges the enormous challenge for livestock farmers and actors all along the supply chain. This recognition enables the stewardship of a rapid, but fair transition away from livestock production towards plant-based food, for example by accompanying farmers and stakeholders through partnerships and training programs. A just transition shall determine the extent to which production should decrease considering the context specificity of livestock producers and their environment (Willett et al., 2019), especially not to harm farmers with restricted livelihood alternatives. The reduction of the livestock sector shall also consider the differences in industrialization levels of global food systems (Gillespie and van den Bold, 2017), focusing on high and medium-income countries where the consumption and production of animal products is often too high, but avoiding nutritional shortage in developing countries (Rasmussen et al., 2021). A just transition should as well consider mechanisms to ensure a fair distribution of animal products across consumers of different wealth within countries.

Future research could generate deeper insights by combining trilateral trade data for feed and animal products with information on intermediary supply chain actors including slaughtering houses, processors, traders, and retailers (Infante Amate and González de Molina, 2013). Global supply chains of feed and animal products are indeed largely dominated by a handful of powerful companies. Folke et al. showed that "Eight companies control at least 54% of the processing or exports of soybeans", including Amaggi, Bunge, Cargill, ADM, and Louis Dreyfus, although ecological impacts of these companies are not always proportional to their market volume (www.trase.earth). Similarly, "74% of the deforestation risk linked to Brazilian beef exports were linked to the top 5 beef exporting companies" (Folke et al., 2019) topped by JBS, Marfrig Global Foods, Minerva, and Mataboi Alimentos (www.trase.earth). This market concentration suggests that capping the quantity of animal products at intermediary stages of the supply chain might be more effective, than waiting for billions of consumers to voluntarily change their habits.

4.3. Limitations

Our input data were subject to the following limitations: Since 2013, the FAO does not release all feed data, as new supply utilization accounts do not include important products such as soy cakes. Fodder crops (e.g. green maize) are not reported by the FAO and were lumped into the category grazing and roughage, because it is calculated as a residual in the applied grazing gap approach (Krausmann et al., 2008). This results in an overallocation of eHANPP to grazing land, and an underallocation to cropland. The relative shares of crop residues used as feed are subject to high uncertainties, as the crop and country-specific factors (crop residues per unit of primary harvest) we used were constant for the entire period. Except for certain countries where crop residues used as feed were downscaled to not exceed the feed requirement, the increase in crop residues used as feed was hence proportional to the production of that given crop, which does not reflect changes over time. The uncertainty then affects the estimated grazing, such that the distinction between crop residues and grazing should be interpreted with care. For comparison, if the total residues used as feed would have been kept constant over the period to the value of 1986, feed from grass and roughage would have been 20 % higher (0.95 Gt dm/yr). We did not include trade in living animals, potentially underestimating the international footprint of animal products, especially imported by the Middle East (Ermgassen et al., 2020a, 2020b). We did as well not consider that dairy cows are eventually also used to produce meat, thereby underestimating the eHANPP of cattle meat and overestimating the eHANPP of milk. We omitted animal products not used as food such as leather and wool, meaning that the impacts linked to these products are included in the footprint of meat and dairy. Not only horses or asses, but also major livestock species such as cattle, mutton, or pigs might not only be kept for meat or dairy, but also for other purposes such as labor, savings, or religion, which are not considered in this study. The proportional allocation of origins and end uses hides how crops from different origins can be used for different purposes (for example, EU soy serves direct human food consumption in the EU while imported soy is fed to animals). We relied on the Monfreda et al. map of the year 2000 (Monfreda et al., 2008), and the FAO gridded livestock map for the year 2010 to adjust product-specific NPP_{pot} for all years, which is problematic if the subnational location of crops and livestock production changed significantly over the period. The allocation of feed crops does not consider differences between animals, for example, if cattle are fed with maize but pigs with soybeans. Similarly, all grazing livestock within a country had the same share of grazing, hence neglecting that cattle might be fed with disproportionally more market feed than goats, sheep or horses. However, this likely does not affect the results fundamentally, as market feed for ruminants is overall low compared to roughage (for comparison, if market feed was fed in priority to cattle before other ruminants, while keeping a minimum of 40 % roughage, market feed for cattle would increase from 7 to 11 % of the global feed requirement of cattle). Although all data is available at the country level, we decided to display it at the world regions level. The definition of our world regions as well influenced the visualization and interpretation of the data. Especially the split between Western and Eastern Europe, which was made for historical consistency, is problematic at least after 2004, when Eastern European countries entered the EU and hence its unified market. Livestock supply chains are often more complex than trilateral structures. Feed and animal products can be reexported before reaching their final destination. For example, the Netherlands is known for important reexports of soybeans to other European countries (Kastner et al., 2011; Lemmers and Wong, 2019). Analyzing the influence of reexporting countries on the global livestock supply chains would also be of interest. A full estimation of the uncertainty of footprinting studies however still requires the development of new methodologies, which were beyond the scope of this study.

5. Concluding remarks

Decreasing the ecological impact of livestock is a major lever to reduce agriculture's impact on ecosystems. So far progress has been far below what is needed to align with climate and biodiversity conservation goals. We saw that livestock induced about two-thirds of agriculture's pressure on ecosystems. Livestock's pressure on ecosystems is increasingly linked to the international trade of feed and animal products. Between 1986 and 2013, the pressure on ecosystems linked to trade in animal products has been catching up with pressure on ecosystems linked to trade in feed. Our trilateral approach suggests that action is needed at all stages of global feed and animal product supply chains, and offers a method to monitor the ecological impacts of such interventions and their international consequences. Ambitious measures to reduce the impacts of the livestock system all along the supply chain, such as capping livestock production and sales in overproducing and -consuming countries, will be required for a rapid and just socio-ecological transformation of the livestock sector.

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CRediT authorship contribution statement

Nicolas Roux: Conceptualization, Methodology, Formal analysis, Writing - Original Draft.

Lisa Kaufmann: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

Manan Bhan: Conceptualization, Formal analysis, Visualization, Writing - Review & Editing.

Julia Le Noe: Writing - Original Draft, Writing - Review & Editing.

Sarah Matej: Conceptualization, Writing - Review & Editing.

Perrine Laroche, Writing - Review & Editing.

Thomas Kastner: Methodology, Writing - Review & Editing.

Alberte Bondeau: Formal analysis, Writing - Review & Editing.

Helmut Haberl: Conceptualization, Writing - Review & Editing, Supervision, Project administration.

Karlheinz Erb: Conceptualization, Writing - Review & Editing, Supervision.

Data availability

The HANPP and eHANPP data is further explained in the linked Data in Brief article.

Country and product level HANPP Data can be visualized and downloaded here https://ijsadihsadoaisjd.shinyapps.io/shiny_app_hanpp_all_lu_types/

The country and product level bilateral and trilateral eHANPP data can be downloaded under https://doi.org/10.5281/zenodo.6617859.

Data availability

The data is available in attached Data in Brief article and under the link pasted at the end of the article.

Declaration of competing interest

None.

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