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Beyond the borders – burdens of Swedish food consumption due to agrochemicals, greenhouse gases and land-use change

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A R T I C L E I N F O

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A B S T R A C T

Sweden's environmental policy aims to solve domestic environmental problems without increasing environmental and health impacts overseas. Realizing this aim requires an indicator system with a consumption-based (or "footprint") perspective that captures both local and global impacts and their development over time. In this paper, we present a set of novel footprint indicators to measure environmental pressures from Swedish food consumption. The indicators are calculated by combining data and statistics on agrochemicals and deforestation emissions with EXIOBASE3, a global Multi-Regional Input Output (MRIO) database with a unique and high level of product detail across countries. We estimate the use of pesticides and antimicrobial veterinary medicines associated with current Swedish food consumption and compare those footprint indicators with the EU-28. Carbon emissions from deforestation are calculated with a land balance model and included in the overall carbon footprint of food. We find that Sweden, with its large reliance of food imports, exert a significant agro-chemical and climate footprint overseas, mainly in the EU and Latin America. We point to a need for better data and statistics on the use of pesticides, veterinary medicines and agrochemicals residuals (especially in developing countries) as well as improved spatial data on agricultural activity to further reduce uncertainty in the environmental footprint of Swedish food consumption.

1. Introduction

In the past 15 years, liberalization of international trade, economic specialization and increasing importance of emerging economies have led to reorganizations of supply chains at the global level (Wood et al., 2018). Food is no exception: between 2000 and 2015, volumes of agricultural commodities traded on the international market increased by 127 percent, to 2.2 billion tonnes (Bailey and Wellesly, 2017). Today, just under a quarter of all food for direct human consumption is traded on international markets, as compared to roughly 15 percent in 1990 (d'Odorico et al., 2014). With global agriculture being the largest user of land on the planet, and the cause of multiple environmental pressures – from expansion of agricultural land leading to greenhouse gas emissions and biodiversity loss, to intensification through increased use of fertilizers and chemicals leading to water and air pollution (Foley et al., 2011) – a relevant question is how increased agricultural trade is linked to these environmental impacts. While increased trade may reduce the use of land, water and other resources, by shifting production to areas with higher yields (Kastner et al., 2014) and water use efficiency (Dalin et al., 2012), it may also displace agricultural production to regions with laxer environmental regulations, e.g., causing deforestation (Cuypers et al., 2013; Henders et al., 2015), health and environmental impacts from pesticide use (Ecobichon, 2001) and eutrophication (Hamilton et al., 2018).

Similar to most countries, Sweden monitors the environmental pressures arising from production and consumption processes within its own territory. This is manifested in 16 environmental goals that describe the state of the Swedish environment, and that are to be met within one generation. As an umbrella, the overarching "Generation Goal" states that the overall aim of Swedish environmental policy is to hand over to the next generation a society in which the major problems in Sweden have been solved, without increasing environmental and health problems outside Sweden's borders. Still, data to monitor progress and support implementation

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of the Generational goal is still lacking. We know that Swedish food consumption and food trade patterns have changed considerably over the last decades, mainly towards products with larger environmental footprints. Consumption of high-value food such as meat, fish, refined dairy products, vegetables, fruit and coffee has increased strongly, in contrast to low-value food, e.g. fresh milk, flour and potatoes. Changing diet patterns also includes an overall increase in food consumption and most significant is the strong growth in protein supply from the food system, increasing by 50 percent between 1960 and 2010 (Jordbruksverket, 2015a).

Historically, Swedish food trade has been low, but it started to grow significantly in the 1990s, partly as a result of Sweden becoming a member of the European Union in 1995 (Jordbruksverket, 2011). Between 1995 and 2015, food import value has increased by more than a factor four, and today it is dominated by fish, vegetables & fruits, meat and beverages. Food export value has grown by more than a factor five (although from a low level) in the same period and is dominated by the product groups fish, grains and beverages (although two important food exports—fish products and coffee—are to a large extent re-exported after being processed in Sweden). As per many European countries, Sweden today can be described as a high-income country with a large deficit in its food trade (Tukker et al., 2016).

Given this backdrop, the aim of this paper is to provide data on the Generational goal in relation to Swedish food consumption. We estimate the use of agro-chemicals (pesticides and antimicrobial veterinary medicines) associated with current Swedish food consumption and compare those footprint indicators with the EU-28. We furthermore calculate emissions of greenhouse gases, including carbon emissions from land-use change in food's carbon footprint. By focusing on environmental pressures that have previously been incompletely covered by consumption-based footprint analysis – agrochemicals and tropical deforestation – we also contribute to method development. We show that Sweden, with its large reliance of food imports, put significant agro-chemical and climate footprints overseas, not least in developing countries.

This paper is part of a larger research effort, through the research project PRINCE, aiming to monitor progress towards Sweden's Generation Goal by developing a system of macro-level consumption-based indicators for a wide range of environmental pressures, including greenhouse gas emissions, chemical pollutants and use of resources such as land, water and fish. This system is based on environmentally extended multi-regional input-out (EE-MRIO) data tables and includes environmental pressures not earlier covered in consumption-based studies (e.g. emissions from land-use change, emissions or use of hazardous chemicals).

2. Material and methods

This section includes a short description of the EXIOBASE EE-MRIO database and how data and statistics of agrochemicals and emissions of carbon from deforestation have been linked to EXIOBASE to calculate the use of pesticides and antimicrobial veterinary medicines and emissions of greenhouse gases, including carbon emissions from land-use change, associated with current Swedish food consumption.

2.1. EXIOBASE 3

EXIOBASE is an EE-MRIO model that has been developed within the EU projects EXIOPOL, CREEA and DESIRE with the objective to provide a global EE-MRIO database for environmental analysis of global economy and trade. The latest version, EXIOBASE 3, has a time series of EE-MRIO tables from 1995 to 2011 for 28 EU countries, 14 other major economies and five rest of the world regions. Compared to other EE MRIO databases, EXIOBASE has a higher level of sectorial resolution (200 products, 163 industries for all countries and regions included). Particularly important for this study is the fact that EXIOBASE divides the agricultural sector into eight primary crop sectors and six primary livestock sectors (compared to many other MRIOs, which only has one aggregated agriculture sector; Hubacek and Feng, 2016).

A detailed description of the disaggregation of the agricultural sector in the supply and use tables of EXIOBASE is provided in Wood et al., (2014) and Wood et al., (2015). To shortly summarize, FAOSTAT data on production volumes is complemented by detailed trade data and supply and use coefficients from the AgroSAM model (Müller et al., 2009) in order to inform the disaggregation. The EXIOBASE model also includes a large number of environmental extensions, including emissions from combustion and non-combustion, greenhouse gases, emissions of nutrients from agriculture and resource accounts (water, land and materials). For a detailed description of the latest version of EXIOBASE used here (v3.4), see Stadler et al. (2017). Here we use a symmetric IO table (see section 2.3) in industry by industry form based on the industry technology assumption (Majeau-Bettez et al., 2014) and in monetary units.

Whilst the full EXIOBASE dataset only runs to 2011, a “now-casted” dataset was also constructed to 2016 using partial information (trade data to 2014, macroeconomic accounts data to 2016, and trends in coefficient change). The full description of the interpolation and balancing is included in Stadler et al. (2016). Here we use the 2013 economic data, and some “now-casts” of environmental pressures, combined with our own dataset on chemical use and land-use change (see below).

The advantage of an EE-MRIO, compared to physical-based trade models, is that it covers the whole economy (including highly processed food products and sectors using agricultural products as intermediate inputs), thus enabling the tracking of resource use and environmental impacts along complex international supply-chains, to final consumers. As such, they are well suited for assessments of the environmental impacts of consumption (Hubacek and Feng, 2016), in line with the focus of Sweden's Generational Goal.

However, while the complete coverage of all upstream environmental impacts offered by EE-MRIOs has advantages, it also means that the final accounts include highly indirect impacts, such as environmental impacts associated with imported food eaten by Chinese construction workers, serving the country's growing production industry, exporting electronics and other goods to Sweden. (Hubacek and Feng, 2016). The possibility of implementing policies for reducing these impacts are very limited (barring overall reductions in consumption). From a policy perspective it may therefore be more relevant to assess the environmental impacts from agricultural production associated only with Swedish food consumption, where policies such as food carbon taxes (Wirsenius et al., 2011; Säll and Gren, 2015), procurement of organic food (Regeringskansliet, 2017), or corporate zero-deforestation policies (Lambin et al., 2018) may be employed to reduce the environmental impact of supply-chains feeding Swedish consumers. Hence, here we present results primarily for the environmental pressures arising from food consumption, which we define as primary food products (eight crop, six livestock, fish sectors), processed crop and livestock products (eleven sectors, including beverages), plus the ‘Hotels and restaurants’ sector. Still, for comparison, we will also show results for the full impacts of agricultural production arising from all Swedish consumption.

2.2. Environmental extensions, choice of indicators and data

2.2.1. Pesticides

Use of Herbicides, Fungicides & Bactericides (in the following referred to simply as Fungicides) and Insecticides were chosen as indicators for monitoring potential environmental and health impacts due to pesticide use in agriculture associated with food consumption in Sweden and other EU countries. These three indicators give limited information of the potential adverse effects of pesticide use, as pesticides vary in their toxicological properties and are used in doses from a few grams to several kilograms per hectare. Some EU countries (Germany, France, Denmark) have started to measure pesticide use as a treatment frequency index (TFI), defined as the number of pesticide applications per hectare and year in relation to a standard dose for each authorized use (Lamichhane et al., 2016). A similar indicator (number of hectare dosages) are used in Sweden in following up the use of pesticides in agriculture for the national environmental goal "Non-toxic Environment"[1]). However, as discussed by Persson et al. (2018), indicators for coherent and continuous monitoring of chemicals associated with countries' production and consumption of goods and services require data from databases that are openly available, regularly updated, have an international coverage and are possible to link to different economic sectors. Therefore, data were collected from FAOSTAT which is the major open global data source of agricultural pesticide use, although country coverage and time series are incomplete as many countries do not deliver statistics to FAOSTAT (FAOSTAT 2018).

Data on pesticide use (as *tons of active ingredients*) was collected for year 2013 and this data is the aggregated sum per country divided between use of Herbicides, Fungicides and Insecticides, respectively. In EXIOBASE, these data are allocated to the eight crop cultivation sectors based on their relative economic output. We assumed that pesticide use on permanent pasture is very small or zero, and thus no pesticide use was allocated to production on this land category. For countries lacking data, we made assumptions based on data on pesticide use from similar countries and for whole regions, using countries or regions averages, and for countries with incomplete time series, we used the latest year with data (which for most countries was a few years previous to 2013). We found FAOSTAT's data on pesticide use in China to be unreasonably high, indicating that data are reported as use of products and not as use of active ingredients and we adjusted China's data for this. Table S1 in the Supplementary Material gives an overview of how data gaps were handled.

2.2.2. Antimicrobial veterinary medicine products (VMPs)

The extensive use of antimicrobials in human and veterinary medicines in recent years has accelerated the emergence and spread of resistant microorganisms (WHO, 2015), and the prudent use of antimicrobials in both veterinary and human medicines is one of the main EU agricultural policy areas (EMA, 2015). The European Medicine Agency has developed a harmonized system for collecting and reporting data on the sales of antimicrobial veterinary medicinal products (VMPs) in European countries and since 2010, the European Surveillance of Veterinary Antimicrobial Consumption (ESVAC) reports yearly data.

Data on sales of VMPs in the animal sector was collected from this yearly data-report (EMA, 2015) as an aggregated sum per country (as tons of active ingredients) and in EXIOBASE, allocated to the four animal production sectors (cattle farming, pig farming, poultry farming and meats not else classified) based on the relative economic output. In the future, a goal of ESVAC is to provide a standardized measurement of consumption by livestock species (EFSA, 2017), but for now on, we allocated the use by economic output. For data on VMPs use for countries/regions outside Europe we made the assumption that the average European intensity was used, which likely is a conservative estimate.

2.2.3. Greenhouse gas emissions (excluding land-use change)

EXIOBASE 3 contains a full estimation of greenhouse gas emissions across all sectors of the global economy. The GHG emissions from fossil fuel combustion are based on IEA energy balances and emission coefficients, where the fuel combustion by agriculture from the IEA energy balances is disaggregated based on energy use coefficients of different types of agricultural production (see Stadler et al., 2017). In addition, an Agrimodule is used for agricultural emissions where data mainly from FAOSTAT and International Fertilizer Industry Association are used to obtain technical coefficients, manure production, emissions and trade data in mass units. Calculations of methane emissions and nitrogen-related emissions (most importantly nitrous oxide) are based on the guidelines from the Intergovernmental Panel on Climate Change (IPCC 2006 a,b). The outcome from this Agrimodule are: for individual crops, their production, use of nutrients and emission; and for livestock, their production, feed intake, manure production and emissions per animal category. Relevant for this study are the emissions by crop and livestock type which are aggregated to the eight major crop groups and four major animal categories, for each country/region of EXIOBASE3 (for details, see Merciai and Schmidt, 2016).

2.2.4. Carbon emissions due to land-use change (tropical deforestation) and peatland drainage

We use a simple land balance model, covering five land classes – forests, cropland, pastures, forest plantations and other land – to estimate the carbon emissions associated with agricultural expansion (cropland and pastures) into tropical deforestation (Pendrill et al., 2018). The model is based on the following assumptions: where there is forest loss, (1) if cropland is expanding, it first expands into pastures and then into forests, and (2) if pastures and forest plantation areas are expanding, they are replacing forest land. These assumptions are consistent with studies showing that forests and other natural vegetation is the main source of new agricultural land in the tropics (Gibbs et al., 2010), but also that a lot of cropland expansion occurs on former pastureland (Gibbs et al., 2010; Graesser et al., 2015). Forest loss attributed to cropland expansion is then further allocated to the eight EXIOBASE crop sectors based on their relative expansion.

The land balance model is assessed at national level for the period 2000–2014, for 106 tropical and sub-tropical countries covered by Zarin et al. (2016), except for Brazil and Indonesia, where it is assessed at micro-regional and provincial level, respectively. Spatially explicit data on forest loss and carbon stocks are taken from WRI (2017) and Zarin et al. (2016), where the former was adjusted to exclude forest loss occurring within plantations in Indonesia and Malaysia, and the latter to account for below ground and soil carbon losses (for details, see Pendrill et al., 2018). National level data on net changes cropland, pastures and forest plantation areas, as well as harvested area for the eight EXIOBASE crop sectors, were taken from FAOSTAT (FAO, 2018), supplemented by gross cropland and pasture losses from Li et al. (2017), in order to estimate gross expansion of cropland, pastures and forest plantations. Sub-national agricultural and forest plantation statistics were taken from the Brazilian Institute of Geography and Statistics (IGBE, 2015; 2017), the Brazilian Tree Industry (IBA/ABRAF, 2015), the Indonesian Ministry of Agriculture (2017) and Ministry of Forestry (Dermawan, 2017).

All changes in land class areas are averaged over the three years following the of forest loss, based on empirical evidence on time

[1] See www.miljomal.se/Miljomalen/Alla-indikatorer/Indikatorsida/?iid=139&pl=1.

lags between forest clearing and establishment of soy in Brazil (Gibbs et al., 2015) and oil palm plantations in Southeast Asia (Gaveau et al., 2016). Further, given that the emissions from land-use change is a one-time event, but agricultural and forest plantation commodities flow from the cleared land over time, we amortized the associated carbon emissions over a period of 10 years, implying that the results presented below (pertaining to year 2011), reflect deforestation in the period 2002–2011.

Finally, we estimate carbon emissions from peatland drainage for agriculture, based on country level data in years 1990 and 2008 from Joosten (2010), except for Indonesia, where the analysis is carried out at province level, based on data from Miettinen et al. (2016). We convert the emissions data from Joosten to drained area, interpolate the data in the period 1990–2008 and extend the time-series to 2011 using FAO data on expansion of agricultural land. We then subdivide the cropland area on peat by the EXIOBASE crop categories, in proportion to their harvested area from FAOSTAT (2017). Finally, we estimate carbon emissions from drainage by EXIOBASE sector using the IPCC emission factors (Drösler et al., 2014) for tropical 'paddy rice', 'oil palm', and 'cropland and fallow' (all other crop sectors).

2.3. Calculation of consumption based accounts

We use a Leontief demand-pull model for the calculation of consumption based accounts for Sweden, in line with common applications in IO and LCA research (Miller and Blair, 2009; Wood, 2017). At the core is the intermediate transactions matrix in coefficient terms **A**, which captures the inputs of goods and services for each sector, disaggregated by region of origin. Here, the **A** matrix is taken directly from the EXIOBASE3.4 dataset in industry by industry terms and is in monetary valuation. The data on direct emissions from each sector in each region is a mixture of EXIOBASE3.4 data and compiled data as detailed in section 2.2 above. Emissions are represented as a coefficient matrix **S** which shows the emission level divided by the monetary output of each sector. Finally, the actual consumption by the Swedish population is shown by the final demand vector **y**, which shows the consumption of different goods and services in Sweden by country of final production (only covering household, not-profits and government, as well as capital formation). The full consumption based account **Q**, showing different emissions with a product resolution is then:

$$\mathbf{Q} = \mathbf{S}(\mathbf{I} - \mathbf{A})^{-1}\widehat{\mathbf{y}}$$

where $\widehat{\mathbf{y}}$ is the diagonalization of **y** and **I** is the identity matrix of the same dimension as **A**. Simple aggregation or extraction is then done to **Q** to calculate the consumption based accounts of different sectors. The impacts embodied in imports differentiated from those on the Swedish territory are calculated by disaggregating the emission coefficient matrix **S** into a domestic component and a country of origin component.

We finally complement the analysis with a comparison of the impacts of agrochemicals from Swedish consumption compared to consumption in other EU countries. In order to obtain results here, we use the final demand vector **y** for each EU country as available in EXIOBASE. Finally, it should be noted, that by applying the Leontief inverse $(\mathbf{I} - \mathbf{A})^{-1}$ above, we are allocating the emissions by production sector (e.g. pesticide emissions for horticulture) to the industries using the horticultural products, so that the emissions are expressed per unit of good consumed by household. Hence the allocation from the emissions of production, to those of final goods is completely done by the (monetary) relationships in the IO model, and is based on the relative amount of purchases of goods produced by different industrial/household consumers.

3. Results

3.1. Pesticide footprints associated with Swedish food consumption

The pesticide footprints associated with Swedish food consumption was estimated as 0.30 kg active ingredients (a.i.) of herbicides, 0.17 kg a.i. of fungicides and 0.07 kg a.i. of insecticides per capita, in year 2013. A very large share (75–97%) of food consumption's potential pesticide impacts is embodied in imports, as seen in Fig. 1. For herbicides, one quarter of the footprint is due to domestic use and approximately 60 percent in the European region (including Sweden), while a fifth of herbicides use can be tracked to crop production in Latin America. European crops dominates the fungicide footprint of Swedish food consumption, representing around three quarters of total use. This is a reasonable, as fungicides is the most sold pesticide group in the EU (EU, 2018a) and a large share of Swedish import originate from Europe. Use of fungicides in Swedish agriculture represents only 12 percent of the footprint, while Spain (being one of the biggest fungicide users in the EU) contributes to 16 percent. The insecticide footprint deviates from the two other pesticide footprints as food imports from Europe contributes to a smaller share. Instead, Latin America and Africa stands out, with use of insecticides in these regions' agriculture constituting around half of the Swedish insecticide footprint.

Consumption of food from the product group *Vegetable, fruits & nuts* is responsible for a large share of the pesticide footprints, representing 38, 51 and 46 percent of the herbicide, fungicide and insecticide use, respectively, in Swedish food consumption. Also, *Cultivation of crops nec* (e.g. coffee, tea, cacao) and the product group *Processing of food products not else classified* contribute significantly in all the three pesticide indicator results.

In Fig. 2, the calculated food-related pesticide footprints for EU-28 are presented (gram a.i. per cap), both as a consumption-based footprint and a territorial use (i.e. production-based). Generally, Nordic and Eastern European countries are on the lower side of the EU average for consumption, while western and Mediterranean countries score above the EU average.

Comparing these consumption-based indicators with a commonly used agri-environmental indicator, kg active ingredient per hectare cropland, compiled as ten-year average by Lamichhane et al (2014), indicates that countries with high pesticide usage in agriculture (e.g. Belgium, France, Italy, the Netherlands, Spain) also tend to have higher pesticide consumption footprints. The obvious explanation for this is that a major part of these countries' food consumption is produced domestically. Sweden's ranking of its fungicide and insecticide footprint below EU-average can partly be explained by a low use of those two pesticide groups in agriculture, in a ten-year average usage of insecticides and fungicides per hectare cropland, Sweden are among the three lowest countries in the EU (Lamichhane et al., 2014).

3.2. Antimicrobial veterinary medicine products (VMPs)

The VMPs footprint associated with Swedish food consumption was close to 5 g a.i. per capita in 2013, of which 17 percent was due to domestic production. European livestock production constituted the largest share of the Swedish veterinary medicine footprint, accounting for around 70 percent of VMP use, which is expected as most animal products are imported from European countries. The ESVAC statistics on use of VMPs are reported totally per EU country and per livestock population correction unit (PCU) where one PCU is one standardized kg of animal biomass in the country. Sweden are among the three countries with lowest VMP-use per PCU in Europe (EMA, 2015), most of the milk and meat produced in

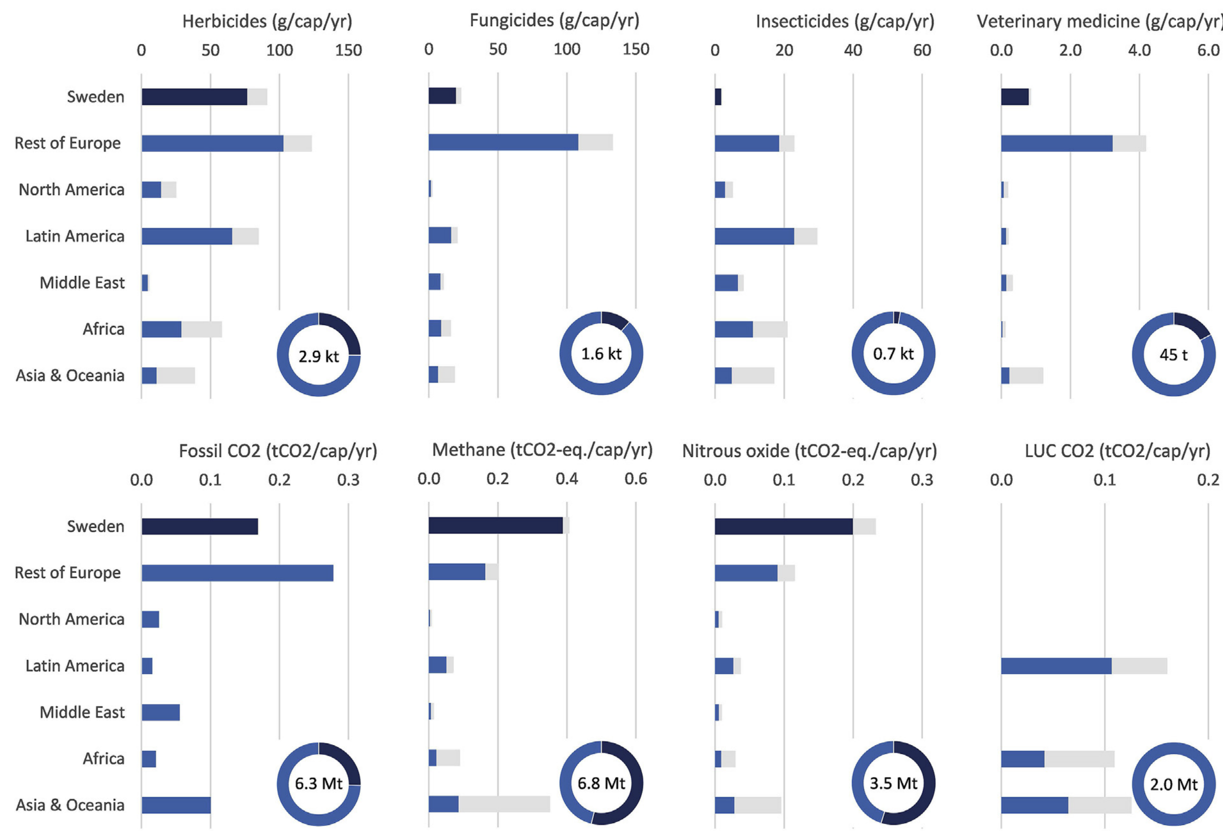

Fig. 1. Per capita footprints for Swedish consumption of herbicides, fungicides, insecticides, veterinary medicine year 2013 (left to right, top row) and emissions of fossil carbon, methane, nitrous oxide and carbon from land-use change year 2011 (left to right, bottom row), by region of production. Blue bars represent footprints for final consumption of food, while grey bars represent the full consumption footprint, covering all final consumption (excluded for fossil CO2, as this is would include all fossil CO2 emissions in the economy). Circle insets show the share of impacts originating from Swedish production (dark blue) versus imports (light blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Sweden are also consumed domestically which explains the low ranking of Sweden when comparing VMPs footprint across EU countries, see Fig. 2. Countries with the highest use of VMPs per PCU in agriculture (Spain, Cyprus, Italy) also comes out significantly higher than the EU average VMP footprints, both for consumption-based and territorial use (per capita).

3.3. *Climate footprint including LUC-carbon emissions*

The total climate footprint of Swedish food consumption was 2.0 tCO_2-eq. per capita in 2011, of which 34 percent was due to fossil carbon emissions, 37 percent methane emissions, 19 percent nitrous oxide emissions, and 11 percent emissions from tropical deforestation (including peatland drainage). For the non-deforestation emissions sources, emissions were roughly equally split between consumption of domestic produce and imports, while emissions from tropical deforestation (by definition) solely stemmed from imports. The sectors of consumption contributing most to greenhouse emissions naturally varied between the different gases and sources: methane emissions mainly resulted from consumption of beef and dairy products, nitrous oxide emissions were relatively evenly spread over different crop and livestock sectors (reflecting overall share of Swedish diets), and deforestation emissions were also dominated by beef (from Latin America) and processed foods (including a large contribution from deforestation for palm oil production in Southeast Asia).

3.4. *Food consumption versus total consumption*

The results presented above all represent the footprint of Swedish food consumption (as delimited in this paper). As can be seen Fig. 1, consumption in food sectors does capture between two-thirds and three-quarters of total use/emissions for nearly all indicators,[2] except for deforestation emissions, where half of the impact stems from consumption in non-food sectors. However, as seen in Fig. 1, there are large differences in this share between sourcing regions. Overall, food consumption captures over 80% of impacts associated with domestic production and EU imports, while for Asia & Oceania food consumption only accounts for 19–35% of total consumption impacts. The latter is hardly surprising, given that Swedish imports of food products from Asia is limited (Jordbruksverket, 2015b), but we can know from previous studies that land-based products can constitute an important input to manufacturing industries in Asia (see Hubacek and Feng, 2016, for a detailed account for China), which in turn is a large source of Swedish overall imports. This partly also explains the lower share of deforestation emissions stemming from food consumption, given that Asia is a key importer of embodied deforestation, both from

[2] Had we included public consumption (e.g., health and education sectors), this share would have been slightly higher, by 4–6 percentage points, but we cannot separate out the consumption of food (i.e., in hospital and school restaurants) from non-food consumption in these sectors.

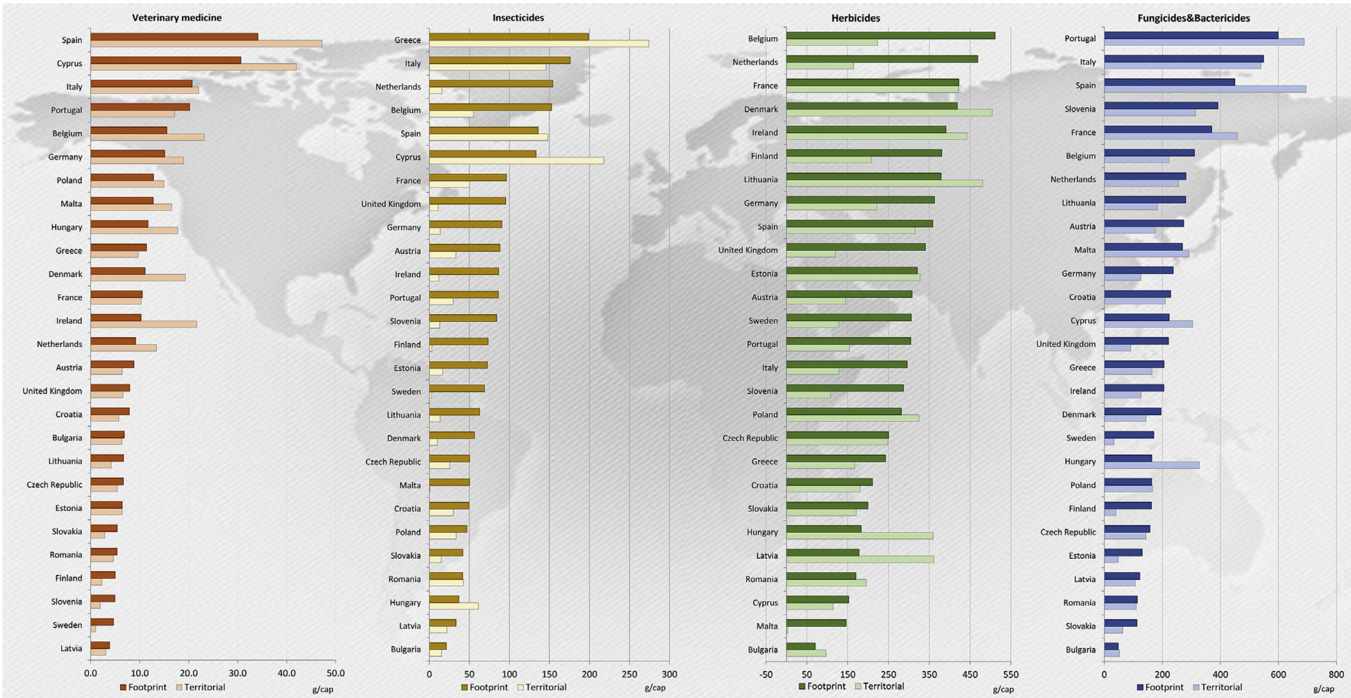

Fig. 2. Veterinary medicine, Insecticide, Herbicide and Fungicide Footprints (Consumption-based, darker colour) and Territorial (Production-based, lighter colour) as gram per capita and EU country, year 2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Latin American soybeans for feed and Southeast Asian palm oil (Henders et al., 2015).

4. Discussion and conclusion

4.1. Data gaps and errors

There are two main sources of error that affects the results presented above: (1) the availability and uncertainty in data underlying the environmental extension estimates, and (2) the approach taken to allocate estimated environmental indicators among different economic sectors.

FAOSTAT is the major global data source for agriculture production and activities but when it comes to pesticides, it has a severe lack of reported data, especially for developing countries. Research indicates increasing pesticide use and dependency in the Global South, e.g. quantified from studies in Vietnam and in sub-Saharan African countries (Hoi et al., 2016; De Bon et al., 2014), a probable development poorly covered by FAOSTAT, indicating that the FAOSTAT data may be underestimating pesticide use in these regions. Developed countries generally have comprehensive pesticide statistics, e.g. the EU reports yearly indicators for pesticide use with statistics that is coherent with FAOSTAT, but a drawback is that these data are not provided at crop level and consequently some allocation method must be chosen to distribute the use to different crops. In this study we have allocated according to the crops' relative economic output, which to some extent is arbitrary. It is reasonable to assume some correlation between economic output and use of pesticides, but it is unlikely to be a relation one to one. Still, we judge this to be the best allocation to be made given the lack of higher resolution data.

Data on use of antimicrobials in livestock production is missing for many countries, stemming both from lack of publicly funded monitoring systems and the reluctance of some business stakeholders to provide reports of antimicrobial sales (Van Boeckel et al., 2015). The harmonized program ESVAC for collecting data on VMPs sales in European countries has led to huge improvements and created a uniform methodology in VMPs monitoring across European countries (Chantziaras et al., 2013) and since 2009, has shown decrease in antibiotics use in the EU livestock (Topp et al., 2017).

The results presented here are on the conservative side as we have assumed that use of VMPs outside the EU follows average EU intensity. In 2006, the EU implemented a total ban on antibiotic growth promoter use in livestock production, but in most countries around the world, antibiotics in agriculture is used not only for disease prevention but also for growth promotion, which imply larger uses. Since the dominating share of meat and dairy products imported to Sweden has European origin, the assumption of average EU intensity in rest of the world can be justified in this study, but the very large uncertainties on global consumption of antimicrobials in livestock production discussed by Van Boeckel et al. (2015) is an important observation.

An important limitation in the EU data is that the VMPs are not collected separately for livestock categories, and here we allocated VMPs use in relation to the relative economic output from the livestock sectors. Hopefully, another allocation method can be used in the future, at least for EU countries, as the ambition by ESVAC is to provide data per animal species (Chantziaras et al., 2013; EFSA, 2017).

For deforestation emissions, the recent advances in utilizing remote sensing data has dramatically improved the quality and availability of data of forest loss and carbon stock changes at the global level. However, this data does not come without caveats. The data used for deforestation area measures loss of forest, but does not distinguish natural forests from production forests, implying that it also captures forest clearing due to stand rotations (which, over the time horizon of the rotation, does not contribute to net carbon emissions). We have tried to minimize this problem by excluding forest loss in plantations delineated in Indonesia and Malaysia, as well as by restricting the analysis to tropical countries where natural forest loss dominates. Moreover, despite recent advances in combining field-plot data with satellite imagery to estimate biomass carbon stocks, there is still substantial disagreement on the spatial distribution of forest carbon stocks in the tropics (Mitchard et al., 2013).

Turning to the issue of allocation, the land-balance model used to allocate deforestation to agricultural land uses and EXIOBASE sectors aims to capture the proximate drivers of deforestation (i.e., the land-uses replacing forests, rather than the underlying forces causing these land-use changes; Geist and Lambin, 2002). However, because the model is non-spatial, based on relative expansion, it may conflate direct drivers (i.e., land use expanding on previous forest land) and indirect drivers (i.e., land uses expanding and pushing other land uses onto cleared forest land). With the accuracy and consistency of global land cover products still being too poor (especially in forest frontier areas) to allow for a fully spatial analysis of land uses replacing forests (Pendrill and Persson, 2017), we have tried to minimize this problem by reducing the spatial scale of analysis for the two countries accounting for most (40%) of total deforestation in the tropics. Still, even if we would perfectly allocate deforestation to the crops grown on cleared land, we would need trade data to match this spatial resolution (i.e., an understanding of where in tropical countries production for Swedish consumers originated) in order to accurately assess the impact of Swedish consumption on deforestation (Godar et al., 2015). As such, the indicator presented here can be viewed as a measure of risk that Swedish consumption causes deforestation. This, of course, holds also for other indicators where there are variations between producers and/or regions of production within a country.

4.2. Comparing carbon footprint with other studies

The greenhouse emissions from private food consumption was here estimated at 0.72 tCO_2-eq. methane, 0.36 tCO_2-eq. nitrous oxide, and 0.66 tCO_2-eq. per capita, in total 2 tCO_2-eq. per capita and year. This is higher than 1.5 tCO_2-eq./cap/yr estimated by Sandström et al. (2018), though this is largely due to the exclusion of fossil CO_2 emissions due to agricultural commodity production and trade. The estimated deforestation emissions from Swedish consumption are, however, notably higher in their study (0.5 tCO_2-eq./cap/yr vs. 0.2 tCO_2-eq./cap/yr here). This is likely due to differences in data sources and methods: Sandström et al., uses another dataset for deforestation (FAOSTAT) and assume that more deforestation is due to agricultural expansion than what our land-balance model show. The fact that we do a sub-national analysis for Brazil also imply that we allocate less emissions to soybean production (pasture expansion being a more important direct driver of deforestation in Brazil), and as EU is a large importer of Brazilian soybeans, this results in a lower deforestation footprint as estimated here.

Bryngelsson et al. (2016), who used national statistics together with LCA data, and Sjörs et al. (2017) who used individual food dairies, estimated the total emissions at 1.8 tCO_2-eq. per capita and year, and roughly evenly spread between the three gases. On the one hand Bryngelsson et al. (2016) and Sjörs et al. (2017) estimates are based on all food consumption in Sweden (not only private), but on the other hand they base their estimate on LCA data, which typically yield lower emissions estimates compared to input/output analysis. Therefore, the total, as well as the methane and carbon dioxide emissions, seem to match reasonable well. However, the nitrous oxide emissions seem to deviate significantly (estimated to total 0.6 tCO2-eq. per capita in these studies, compared to only 0.36 tCO2-eq. per capita here) and further studies are needed to analyze the reasons behind this discrepancy.

4.3. Agro-chemical footprints – what information do they give us?

Here, we present a set of new consumption-based indicators for estimates of agrochemical footprints and calculate them for Sweden and the EU showing interesting differences between countries. As previously discussed, presently available data limit these agro-chemical-indicators to be calculated only as “driver-indicators” whilst there is a future need to construct also “pressure” and “state” indicators for agro-chemicals. However, an indicator describing use of antibiotics in food production is still very useful. Strong correlations has been shown between consumption levels of antimicrobials and the prevalence of antimicrobial-resistant *Escherichia coli* in pigs, poultry, and cattle (Chantziaras et al., 2013) and the risk for ecosystem damage increases with larger use as a high percentage of animals' antibiotics intake is excreted via urine and feces, and thereby increases the risk to enter the environment when livestock manure is spread in crops and pastures (Zhang et al., 2014).

The average consumption-based VMPs footprint for EU-28 is calculated as roughly 11 g a.i. per capita in year 2013 and as earlier shown, countries scoring high for this indicator are among the countries that show a high use in their animal production. Sweden's consumption-based VMPs footprint is roughly 5 g a.i. per capita, less than half of EU average and among lowest in this comparison, and a result of a low use of antimicrobials in Swedish livestock production. Already in 1986, Sweden forbid the use of antibiotic growth promoters in agriculture, 20 years earlier than the ban in the EU. National surveillance started in the late 90s, and an on-going program strives for holding down antibiotics use, in human as well as in veterinary medicine. Antimicrobials use in human medicines in Sweden in 2013 corresponds to an average of around 6.5 g a.i. per capita (SWEDRES-SWARM, 2013). Interestingly, the Swedish VMPs consumption-based food footprint is thus in the same order of magnitude.

The pesticide footprints estimated here target drivers of chemicals pollution, by informing about use of pesticides' active substances. This is indeed a very coarse indicator as the negative effects from pesticides on health and environment vary largely between different substances, by orders of magnitude (Fantke et al., 2012; Nordborg et al., 2014). For pesticides, pressure indicators need to be developed and for this, pesticide and crop specific data is crucial. The need for more comprehensive data for establishing state indicators to follow up agriculture's use of pesticides are highlighted by e.g. Stehle and Schultz (2015) who investigated the exposure of surface waters to insecticides on global scale showing that very large areas of cropland around the world lack pesticide monitoring of surface waters. Similarly, Milner & Boyd (2017) argues for safe environmental limits for pesticides at landscape level, exemplified by findings from the United Kingdom showing a strong increase of doses of neonicotinoids, an insecticide group related to decline of pollinators, in agricultural landscapes. In the EU, the Directive 2009/128/EC on sustainable use of pesticide states that all member states shall establish a set of harmonized risk indicators which needs detailed and harmonized data on active ingredients' use and information on model of application and exposure rates. However, as these risk indicators have not yet been agreed, the work on this Agri-environmental indicator has been put on hold for the time being (EU, 2018).

Although pesticide use indicators are coarse and can be criticized, an observation on insecticides related to the EU food consumption is in place. As shown in Fig. 2, in many EU countries the consumption based insecticide footprint comes out much higher than the territorial footprint, indicating that there is much insecticide use embedded in food imports. For Sweden, this is very distinct – less than five percent of insecticide use is territorial and the majority of the footprint is due to insecticide use in developing countries and this is different picture from herbicides and fungicides. As Stehle and Schultz (2015) point out, the world-wide damage of insecticides on biodiversity and ecosystems is probably underestimated due to the lack of monitoring, not least in developing countries where environmental regulating control often is low.

4.4. Conclusions

This study adds environmental indicators for agrochemicals and deforestation to the EE-MRIO data base EXIOBASE and present pesticide footprints, antimicrobial veterinary medicines footprint and carbon footprint, including land use change, for Swedish food consumption, thereby introducing environmental pressures not earlier covered in consumption-based studies of food. We find that:

- More than three quarters of Sweden's pesticide footprint is embedded in imports, with vegetables and fruits as an important product group. For the insecticide footprint, a significant share is embedded in imports from developing nations. In comparison with other EU countries, the relation between the consumption-based and territorial-based pesticide footprint is larger for Sweden due to Sweden's large food imports and low pesticide use in domestic agriculture.
- In the EU perspective, insecticides deviates from the two other pesticide groups as food imports are responsible for relatively larger insecticide use overseas.
- More than 80 percent of the use of antimicrobials in livestock production for sustaining the Swedish food consumption takes place beyond national borders. In an EU comparison, the Swedish VMPs footprint per capita ranks low due to a prudent use of antibiotics in domestic agriculture.
- The total climate footprint of Swedish food consumption in 2011 was 2.0 tCO_2-eq. per capita including emissions from tropical deforestation. Around 60 percent of greenhouse gas occurs overseas, most significantly for LUC-CO_2 (all by definition) and fossil CO_2 (three quarters), while for methane and nitrous oxide approximately half of the emissions are embedded in imports. And while deforestation accounts for only 11% of the climate footprint of Swedish food consumption, the total impact of all Swedish consumption on deforestation emissions is in the same magnitude as domestic emissions of methane or nitrous oxide in agriculture.
- Most of the food related environmental impact in European countries caused by Swedish consumption falls on the direct consumption of food in Sweden. However, for other regions (especially Asia) a large share of impacts in agriculture due to Swedish consumption are indirect, through consumption in other sectors.
- Lack of data and statistics on use of agrochemicals as well as monitoring of pesticide residuals in ecosystems, not least in developing countries where global agriculture is foreseen to expand, is a major hindrance for analysis of chemical pollution caused by food consumption.

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Appendix A. Supplementary data

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