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Indicators for national consumption-based accounting of chemicals

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ABSTRACT

Increased chemical use is causing a growing number of environmental problems and chemical products are pervasive in societies within animal and crop-based agriculture, in industrial processes and in households. National environmental targets, as well as the global chemical-related goals in the 2030 Agenda, call for the monitoring of chemical use and emissions. The growing international trade of goods, where use and regulation of chemical inputs vary highly between countries, complicates measurements. This paper addresses these issues by deriving a set of indicators on chemical use and emissions and connect the global impacts to a country's total consumption, here using the case of Sweden. The indicators are based on a hybrid model combining the multi-regional input-output analysis database EXIOBASE with data from the Swedish System of Economic and Environmental Accounts together with a novel set of environmental extensions. A review of databases is conducted and discussed in relation to the driver-pressure-state-impact-response (DPSIR) framework for indicators. Five indicators are calculated, showing the chemical use and emissions connected to consumption, both within a country and abroad. The indicators are: use of hazardous chemical products, use of pesticides, use of antimicrobial veterinary medicines, emissions of hazardous substances, and of the potential toxicity of these emissions. The results show that the impact of Swedish consumption in terms of use and emissions of hazardous substances is largely taking place outside the Swedish borders. Only 10–24% of the pressure from Swedish consumption is shown to occur within Sweden's borders, depending on the indicator. The use of hazardous chemical products and veterinary medicines related to Swedish consumption primarily takes place in other EU countries, whereas the use of pesticides as well as reported emissions of pollutants occur mainly in countries outside the EU. The results highlight the need for improved international accounting of chemical flows, as well as for strengthened policy frameworks to address cross-border impacts of consumption of hazardous chemical products.

1. Introduction

Everyday life in contemporary societies depends on the use of over 100 000 different chemicals. Poor control and management of these chemicals result in pollution and exposure, with negative impacts on human health (Pruss-Ustun et al., 2016, 2011), ecosystems (Diamond et al., 2015; Walker et al., 2012) and economies (UNEP, 2013). The increasingly complex supply chains in global trade together with the transboundary nature of chemical pollution mean that lack of chemical control and management in one location may affect human health and the environment at large distances from the source.

The European Union (EU) has set the goal to achieve a “non-toxic environment” (EU, 2013). There is also a global goal of minimizing risks from chemicals to human health and the environment by 2020 (SAICM, 2006). Sweden has a so called generation goal which aims “… to hand over to the next generation a society in which the major environmental problems in Sweden have been

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solved, without increasing environmental and health problems outside Sweden's borders" (SEPA, 2015). In order to reach such goals, indicators that can monitor progress in reducing chemical pollution at the macro-level are required. Acknowledging that it is practically impossible to measure the entire impact of hazardous chemicals in a country, this study aims at finding a set of chemical indicators that can be used to monitor the development in relation to policy targets on chemicals management at a macro level.

Previous work has identified the need for multi-regional input-output (MRIO) analysis (Brolinson et al., 2010; SEPA, 2013), allowing for pollution embodied in imports from other regions to be included in the calculations. This gives a "consumption-based approach" to monitoring chemical use and release, which is required in order to monitor the generational goal as defined above. MRIO tables are based on the same accounting system as used in national accounts of countries (EU, 2014; UN, 2014), and by basing indicators on such national accounts, existing structures for annual reporting and feedback to the political system can be used. Several studies of environmental impacts and resource use from consumption using MRIO have been published the last years (e.g. Ivanova et al., 2016; Wiedmann et al., 2015). They have most often used carbon footprints and indicators related to resource use as environmental indicators, whereas use and emissions of hazardous chemicals have largely been excluded (Sörme et al., 2016).

This study is part of a project on Policy-Relevant Indicators for Consumption and Environment (PRINCE, 2016) and based on the environmentally extended hybrid model developed in the PRINCE project. The PRINCE model draws on the detail of Sweden's national accounts coupled with information on international flows of goods and services from the MRIO model EXIOBASE. This enables the construction of indicators that reflect embedded pollution along global supply chains, the tracing of those pressures back to the specific producer countries and regions, as well as their allocation to product groups (Palm et al., 2018).

This paper first explores existing databases on physical flows of chemicals in society and discusses which indicators that can be designed based on these. Thereafter, a methodology for adding these data sources as extensions to an MRIO analysis is developed. This includes aggregation of chemical data and extrapolation of data to countries where this is missing. Lastly, results from the suggested indicators for Sweden as a case are presented and discussed.

2. Method

2.1. Data categorization and aggregation

Two perspectives were used to categorize data in the study. To describe the physical flows of chemicals, a product life cycle perspective (see e.g. Finnveden et al., 2009; Hauschild, 2005) was applied, detailing the flows of chemicals from the extraction of raw materials, through production of products, use of chemicals and creation of waste flows (Fig. 1). This perspective was complemented with the driver-pressure-state-impact-response framework (DPSIR) developed by the European Environment Agency (EEA, 2014, 1999). A driver could be the consumption of goods and services, which in turn leads to a pressure when the chemicals are emitted, i.e. chemical pollution. Chemical pollution means higher concentrations of chemicals, altering the state of the environment. Higher concentrations in turn lead to impacts on ecosystems or human health, which could trigger societal responses, e.g. in the form of legislation. Although the goal of society is to limit the chemical *impact*, measuring impact only, runs the risk of discovering unacceptable effects when already a fact and costs for damages and remediation expenses may be haunting (EEA, 2001). In order to safely manage the large number of chemicals used, more upstream DPSIR categories, such as pressure, therefore need to be monitored as well.

For the aggregation of data on chemicals into indicator results, a number of methods have been proposed. Statistics Sweden has developed a method based on the use of hazardous substances reported by industry, which allows for sectoral analyses of chemical use within the country (Fig. 1, input to production). Palm et al. (2006) applied this method to assess the chemical intensity of the Swedish economy. Toller et al. (2013, 2011) used the same method for assessing the Swedish building and real estate sector.

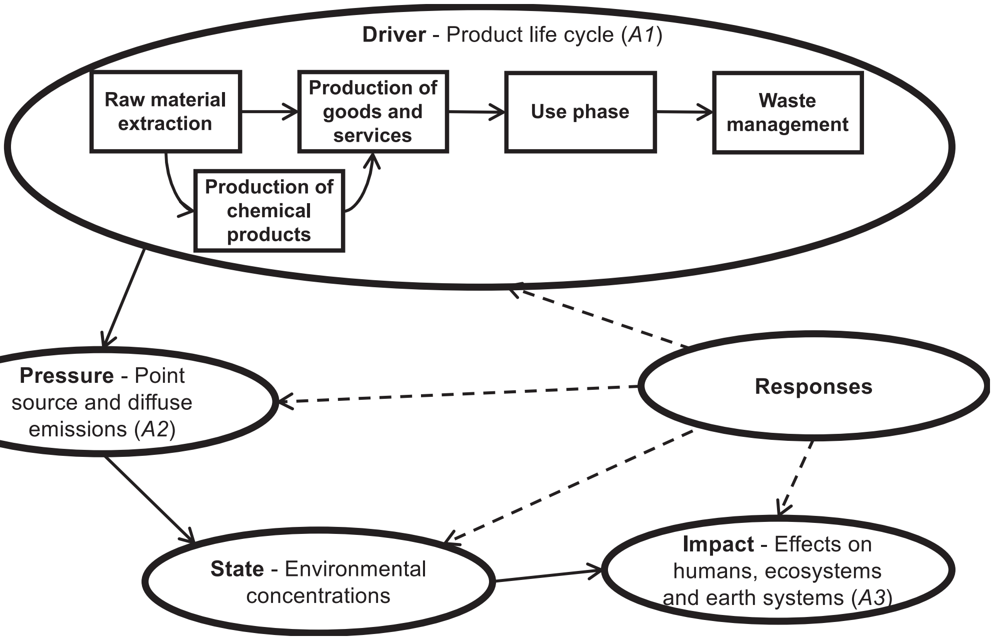

Fig. 1. Physical flows of chemicals shown with solid arrows in a life-cycle perspective and in relation to the driver-pressure-state-impact-response framework (DPSIR), with societal responses shown with dashed arrows. A1-3 refers to the different aggregation methods.

This method can be described as:

$$A_1 = \sum m_{haz} \tag{1}$$

where A_1 is the aggregation in kg of various hazardous chemical products (m_{haz}) for a specific region. The classification of chemical products as hazardous is done based on the EU regulation on classification of substances and mixtures (Regulation (EC) No 1272/2008). A similar approach is also used by Eurostat when reporting on use of toxic chemicals (Eurostat, 2016). The same general approach can also be used for specific chemicals or groups of interest.

Another aggregation method is to, rather than measuring chemical use, enumerate chemical emissions into the environment (Fig. 1, emissions). This was done by DeVito et al. (2015) to assess chemical pollution from the pharmaceutical industry in the United States. Ranson et al. (2015) used the same method for assessing the whole United States' manufacturing industry. This method can be described as:

$$A_2 = \sum m_{em} \tag{2}$$

where A_2 is the aggregation in kg of various emissions (m_{em}) for a specific region. It is possible to differentiate between emissions to different environmental compartments and emissions by different economic sectors.

In order to account for the different levels of hazardousness of chemicals, it is possible to multiply each emission with a characterization factor (CF), e.g. based on the USEtox method (Rosenbaum et al., 2008). USEtox calculates impact indicators for human toxicity and freshwater ecotoxicity at midpoint level. For example, Sörme et al. (2016) and Nordborg et al. (2017) assessed the toxicity of national chemical pollution in Sweden, and Sala and Goralzcy (2013) used the same method for assessing the toxicity of chemical pollution of the EU. The method can be described as:

$$A_3 = \sum CF \times m_{em} \tag{3}$$

where A_3 is the result of the method and CF stands for characterization factors. In terms of the DPSIR framework, this approach transfers pressure data into impact data. Human toxicity and ecotoxicity impacts are considered separately by USEtox (Rosenbaum et al., 2008), so this method can provide $A_{3,\text{humantox}}$ and $A_{3,\text{ecotox}}$, but no aggregation of the two. The CF for human toxicity impacts is expressed in comparative toxic units (CTUh, disease cases/year/kg), the estimated increase in morbidity in the total human population per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer. The CF for ecotoxicity impacts is expressed in comparative toxic units (CTUe, potential affected fraction $\times$ m^3 $\times$ day/year/kg), an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (USEtox, 2017b). Although CFs for organic substances in USEtox have uncertainties of 2–3 orders of magnitude (Rosenbaum et al., 2008), the results from A_3 provide information about the potential impacts of the substances, which A_1 and A_2 does not. To compare, there are more than 10 orders of magnitude difference in CF between substances, implying a high difference in impact that the A_1 and A_2 approaches do not capture.

The aggregation methods A_1-A_3 complement each other. The first method is based on the use of chemical products (a "driving force"), the second method is based on summations of emissions of chemicals (a "pressure"), whereas the third method assesses potential impacts on humans or the environment.

2.2. Identifying data sources

Existing data sources were identified through a survey of global and national databases covering different aspects of the physical flows of chemicals through society, with a focus on data for the case study country of Sweden. The mapping of data sources started out broadly, intending to capture databases that could cover any chemical flows of relevance for Swedish consumption of goods and services (Fig. 1). The identified data sources were evaluated using three criteria, i.e. the data sources should be:

1. Annually updated
2. Publicly available through the internet
3. Organized so that the chemical flows can be attributed to economic sectors

The third criterion is required to connect the chemical flow data to the System of Economic and Environmental Accounts (SEEA) and MRIO models. The identified data sources were further examined in order to establish what type of aggregations of single chemicals or chemical groups into larger groups were possible.

2.3. Linking chemicals data to the MRIO analysis framework

The identified data sources were linked to the PRINCE model, presented in detail in Palm et al. (2018), which is based on a combination of data from the Swedish environmental accounts for Sweden and from EXIOBASE (Stadler et al., 2018; Wood et al., 2015) for the rest of the world. The product groups as well as the EXIOBASE regions that are used in the study are listed in Appendices A and B, respectively.

In order to link the data to the MRIO analysis, the aggregated chemical use or emissions need to be linked to different economic sectors or industries. There are standards for classification of industries (sectors), for example the statistical classification of economic activities in the European Community (NACE), on which EXIOBASE is based. There are different levels of aggregation in the classification schemes, and changes over time mean that the industry classification that is used by chemical databases will likely be different to that of MRIO models. Consequently, the process of allocating the chemicals data likely involves either aggregation or disaggregation of the data into the intended level of the IO models. Disaggregation requires additional information that can be used as a way to split the original chemical data. This data could typically be value added data per industry or production value data per industry, which is used in such a way that the chemical use or pollution will obtain the same proportions at the more detailed aggregation level as the value-added data or production value data. Such a method implies the assumption that physical flows of chemicals have a linear relationship to the economical flows.

In general, chemicals data will not be available for all regions and countries in a MRIO. In such cases there is a need for an extrapolation of data from countries with available data to countries and regions without data, typically using economic data. For example, an extrapolation can be based on the assumption that the emission or chemical use per monetary unit for the specific sector is the same in different countries. This type of extrapolation will, however, typically underestimate emissions from low-income countries (Cucurachi et al., 2014).

3. Indicator development

3.1. Selecting databases

The mapping of databases resulted in a list of 15 sources on physical flows of chemicals (see detailed mapping of data bases in Appendix D). The sources included data on chemical use in different sectors, hazardous waste, different type of emissions, as well as response measures to safely manage chemical flows. Several databases were found to fulfill the three screening criteria. Others were not, most often because the data was not linked to specific economic sectors.

The DPSIR category with the highest number of data sources fulfilling the criteria of this study is drivers. Notably fewer data sources are available for the pressure category. It should be noted that there are also knowledge gaps, for instance regarding chemicals contained in products and the exposure and emissions emanating from these during use, as well as information on the chemicals used in production in international supply chains (Kogg and Thidell, 2010; Nordiska Ministerrådet, 2011).

Data sources available for the state category are even fewer and more fragmented than for pressure. The high number of possible options in terms of which substances to measure in which compartments also limit the possibility to compare data from different countries compiled under different monitoring programs. For these reasons, no state indicator is proposed here. For the impact category, no explicit data sources were identified, although Eq. (3) provides a mean to convert pressure data to impact data. The relative abundance of data sources found here in terms of DPSIR categories is thus $D > P > S > I$. Data sources on response exist but are not easily linked to consumption in specific sectors and mostly of qualitative character (e.g. legislation on chemicals put in place, or risk reducing regulations of different kind). The response category is crucial, since it includes all the measures and policy response that society undertakes in order to address undesired aspects of drivers, pressures, state and impact. These response measures may be directed to a certain sector or economic activity but are not directly linked to consumption, like the other data sources discussed here. Further development of response indicators is likely better done separate from the MRIO modelling (and of course being informed by the results of the indicators in the other DPSIR categories).

Going back to the basic criteria for the data sources (Section 2.2), seven of the identified sources were found to fulfill all the criteria, of which four are sources of data on use of chemicals (drivers), and three contain data on emissions (pressure). Among the databases on use of chemicals, it was decided to move ahead with three: ESVAC, FAOSTAT, and SEEA data from Statistics Sweden. The fourth database – the Eurostat pesticides database – covers only Europe but has the ambition to develop and enhance the contained data. However, as agricultural products and food increasingly are traded globally, it was judged better to use FAOSTAT, which has a worldwide coverage.

In the category of pressure, three databases were found to fulfill all the criteria. Of these, the PRTR and E-PRTR data sources were decided to be used in the further work, together with the modelled data in EXIOBASE (see section 2.3.4). PRTR and E-PRTR include a slightly larger number of chemicals compared to the third emissions data source fulfilling the basic criteria, CLRTAP, and they also include emissions to both air and water whereas CLRTAP only includes emissions to air. However, CLRTAP is indirectly included since emissions factors from CLRTAP are used for calculating emissions in EXIOBASE.

3.2. Suggested indicators

The selected databases were used to construct a set of indicators on chemicals use and emissions, integrated in national accounts (Table 1). Three of the indicators address the use of chemicals (drivers). The first is constructed using the Swedish SEEA. This indicator gives the sum of hazardous chemical products (in different hazard classes) used per sector and can be used to monitor the development and inform the design and follow-up of broad policy instruments by sectors over time. A strength of this indicator is the broad coverage including nearly 100 000 chemical products.

The two other indicators in the driver category are both related to food production: the use of pesticides and the use of veterinary medicines for food. These indicators would serve to, for example, follow changes in chemical use and dependence in food production including use of antibiotics. These indicators represent the currently best available proxy for estimating impact of pesticides and veterinary medicines as a result of consumption on a macro level. In relation to the methods for aggregation of chemicals discussed above (Eqs. (1)–(3)), the data in the Swedish product register, FAOSTAT and ESVAC corresponds to m_{haz} in A_1.

It can also be noted that in the case of pesticides, more thorough and disaggregated information about substances applied is needed for generating impact indicators from pesticide use than what is typically available in FAOSTAT and Eurostat. Since the toxic effects of different pesticides varies by orders of magnitude (Fantke et al., 2012; Nordborg et al., 2014), indicators such as the one proposed here on pesticide use based on sale statistics must therefore be seen rather as a driver indicator for pesticides in food production. If more data were available, use of pesticides could be recalculated to potential impacts of pesticides using emission data aggregated with characterization models (as in Eq. (3)).

The fourth possible indicator represents pressure and covers emissions of hazardous chemicals. Data for this indicator come from the PRTR/E-PRTR databases and from EXIOBASE. The aggregation by weight can be seen as a measure of the amount of

Table 1
The indicators used with the respective data sources.

Indicator	Unit	Data source
Indicators representing drivers in DPSIR		
Use of hazardous chemical products	Metric tonnes of product (per hazard class) per year	The System of Economic and Environmental Accounts, Statistics Sweden and EXIOBASE.
Use of pesticides	Metric tonnes of active substance per year	FAOSTAT
Use of antimicrobial veterinary medicine	Metric tonnes of active ingredients per year	ESVAC***
Indicator representing pressure in DPSIR		
Emissions of hazardous substances	Metric tonnes of active substance per year	PRTR, E-PRTR**, the Swedish PRTR and EXIOBASE
Indicator representing impact in DPSIR		
Potential impact of emissions of hazardous substances, with sub indicators for human toxicity and ecotoxicity	For human health: CTUh (=disease cases per year) For environment: CTUe (=PAF* × m^3 × day per year)	PRTR, E-PRTR, the Swedish PRTR and EXIOBASE for emissions and USEtox for characterization factors

*PAF = potential affected fraction, **PRTR = Pollutant Release and Transfer Register, E-PRTR is the European PRTR, ***ESVAC = European Surveillance of Veterinary Antimicrobial Consumption.

chemicals without considering their specific toxicity, i.e. it does not acknowledge differences in toxic impact between the included substances. A strength of this indicator is that there is data available for all EU countries and several others, and that the EU data follows a common framework. The inclusion of all industry sectors is also important for the coverage of the indicator and that it captures actual emissions instead of proxy emissions is another advantage. Aggregation by weight and aggregation by toxicity using characterization methods can be seen as complimentary, the first resulting in a pressure-type indicator and the latter resulting in an impact-type indicator. Aggregation of PRTR emissions for Sweden using aggregation by weight and the characterization USEtox were recently compared (Nordborg et al., 2017).

Thus, the last indicators suggested here represents potential impact of emissions of hazardous chemicals, using the data on emissions, and then converting the emissions to potential health and ecosystem impacts (Eq. (3)). There are several impact assessment methods available. Since USEtox has been identified as best existing practice (Hauschild et al., 2013), it is suggested to be used here as well.

The indicators we suggest complement each other. They address drivers, pressure and impact. For future work, it would be of interest to follow up also with response indicators, on the development of the overall chemicals management system in producer countries, since such systems are a prerequisite for being able to manage chemicals safely. This type of indicator may have to be of a qualitative character, e.g. if certain basic legislation for chemicals management is in place and is being enforced.

For all indicators, use and emissions of hazardous chemicals connected to Swedish production on the one hand, and the use and emissions connected to consumption on the other hand are reported separately. The production-based use and emissions are those that occur in Sweden plus those caused by Swedish economic actors abroad, e.g. from air transport. The consumption-based use and emissions can occur in Sweden and abroad. The consumption-based emissions are defined as emissions related to Swedish private as well as public consumption plus investments and consist of nationally produced consumption as well as the imported consumption.

A datafile is made available for the complete emission inventory as outlined below, accessible on 10.5281/zenodo.2152872.

3.3. Use of hazardous chemical products

Data on the use of hazardous chemical products per industry for year 2013 was taken from the Swedish environmental accounts (Statistics Sweden, 2016a). Monetary data from EXIOBASE (Tukker et al., 2013; Wood et al., 2015), was used as proxy data in order to estimate the chemical use in other countries, as described below. The hazard classes GHS 05 (corrosive), GHS06 (toxic), GHS07 (harmful), and GHS08 (health hazard) were included. The indicator does not yet include hazard class GHS 09 (environmental hazards), pesticides, pharmaceuticals or cosmetic products. Fossil fuels are also not included since they would dominate the data due to the large volumes consumed (Palm and Jonsson, 2001).

In order to create a vector of the use of hazardous chemical products that fits with the classification and the countries in the EXIOBASE input–output table, the Swedish environmental accounts data of the use of hazardous chemicals were first converted from the newer NACE 2 industry classification to the older NACE 1.1 used in EXIOBASE. This was done by using a correspondence table between NACE 1.1 and NACE 2 from the Swedish national accounts (Statistics Sweden, 2016b). To obtain the same classification level as the 163 industries level used in EXIOBASE, the environmental accounts data were allocated to the 163 industries in the same proportions as the monetary value of the purchases of products that these industries make from the chemical industry. Secondly, using the above-mentioned monetary and physical flow of chemicals per the 163 industries in Sweden, it was possible to calculate the amount of chemicals used per euro purchased chemicals in the Swedish industries. This intensity vector was subsequently used to calculate the amount of chemicals used in the other countries represented in EXIOBASE, and for each of the industries in these countries, by multiplying the intensity for a certain industry with the value of the purchases of chemicals in that industry, for each country (data on the value of the purchases of chemicals per industry and country from EXIOBASE). It should be noted that such an approach assumes equivalence of product groups between countries in EXIOBASE (i.e. that the type of chemicals produced in Sweden are the same as those produced in China), as well as ignoring potential price differences between countries (where an average market exchange rate is the only pricing correction between countries). These two effects are likely to partially offset the expectation that Sweden has less use of chemicals per unit of production than its trading partners. Further work on international data sets is clearly required in order to quantify the impact of such assumptions.

3.4. Use of pesticides

Data on pesticide use in the agricultural sector per country was taken from statistics from the Food and Agriculture Organisation of the United Nations for the year 2013 (using “total pesticide use in tonnes of active ingredients”) (FAOSTAT, 2017). In the statistics, many countries report sales data as a proxy for the actual use of pesticides. Information on actual quantities applied to fields and specific crops is thus not available in FAOSTAT. We assumed that there is negligible use of pesticides on pastures, and for each country where data was available, the total pesticide use in the agricultural sector was therefore allocated to the country's crop groups (based on the EXIOBASE classification) according to their economic intensity.

Pesticide data in FAOSTAT from most EU countries are generally reported with annual updates and they agree well with corresponding EU data in the database EUROSTAT and also with the Swedish national chemical statistics. For other regions in the world, there are gaps in reported pesticide use, and FAOSTAT reports that there is a high rate of non-responses (FAOSTAT, 2017). We filled the data gaps by assuming that the intensity (calculated as pesticide use per hectare) was the same as in countries with similar conditions in the region for which data is available, see Cederberg et al. (2018) for a detailed description of data gap handling.

3.5. Use of antimicrobial veterinary medicine products

Data on the use of antimicrobial veterinary medicine products (VMPs) in the animal sector per country for the year 2013 was taken from the European Surveillance of Veterinary Antimicrobial Consumption (ESVAC) that has developed a harmonized system for collecting and reporting data on the sales of veterinary antimicrobial agents in European countries. The indicator used is “total VMPs use in tonnes active ingredient”, although sales data is an often-used proxy. ESVAC reports the data as total use per country for food producing animals and as milligram active ingredients used per animal population correction unit (PCU). The PCU is calculated for each country based on the size of its animal population (EMA, 2016).

Data on each country's use of VMPs for food-producing animals were added to EXIOBASE and the total VMP use was allocated to the agricultural sub-sectors cattle farming, pig farming, poultry farming and “Meats not elsewhere classified”, based on the economic activity in each of these in relation to the total animal sector in the country. In the future, a goal of ESVAC is to provide a standardized measurement of consumption by livestock species (EFSA, 2017), but for now we allocated the use by economic output. For data on VMPs use for countries/regions outside Europe that lack data on VMPs, the average European intensity was used for all countries, which is likely to be a conservative estimate.

3.6. Emissions of hazardous chemicals

Emissions data for the year 2013 were extracted from EXIOBASE, which originates from country inventories and reports of the United Nations Framework Convention on Climate Change, with harmonization across emission factors, activity data and accounts to give global coverage (Stadler et al., 2018). In addition, data from the E-PRTR database and OECD's PRTR database (for US and Japan) were used to complement the existing emissions data in EXIOBASE. The PRTR databases contain emission data to air and water for large point sources with defined thresholds for different substances (EEA, 2016; OECD, 2017). All emissions of chemicals from the E-PRTR database that could be linked to characterization factors (see below) were included, and from the OECD database only emissions of the substances that were also included in the E-PRTR database were used. A comparison was made between air emission data from EXIOBASE and the PRTR databases for those chemicals for which both data bases had data for the same substance. The emissions in the EXIOBASE were higher for all chemicals except hexachlorbenzene. This is probably because the PRTR databases only includes emissions from point sources over certain thresholds, why the EXIOBASE data is considered more accurate. For air emissions from the PRTR databases, we therefore excluded the emissions already included in EXIOBASE, except for hexachlorobenzene where we instead used the PRTR data. For emissions to air, the number of chemicals included are 21 from PRTR and 17 from EXIOBASE. For emissions to water, 56 chemicals from PRTR were included (see Appendix C).

For the countries and regions that did not have data in PRTR, the corresponding data was estimated by designing an average country with chemical intensities per chemical and per industry, calculated as the sum of all E-PRTR countries per chemical and per industry, and then dividing these data with the total production value per industry of these same countries. These intensities were multiplied with the production value per industry for the country or region in question to calculate the emissions per chemical and industry for that particular country or region. Production values were taken from EXIOBASE for the year 2013 (Stadler et al., 2018). The emissions of hazardous chemicals were aggregated by weight following the A_2 approach (Section 2.1). As per the use of chemical products, the gap-filling approach here is subject to both product aggregation and pricing error, but due to the relatively higher coverage of substance by EXIOBASE is less likely to affect results significantly.

3.7. Potential impacts of emissions of hazardous chemicals

For the calculation of potential impact of hazardous chemicals on human health and the environment, the emissions of hazardous substances, described above, were aggregated using characterization factors from USEtox (Fantke et al., 2017; Rosenbaum et al., 2008) as in the A_3 approach (Section 2.1). Characterization factors from USEtox version 2.02 were used (USEtox, 2017a). When matching emission data and characterization factors, some assumptions needed to be made. A presentation of these and a list of the resulting characterization factors are found in Appendix C (see also Nordborg et al., 2017, for a more detailed discussion).

4. Indicator results

4.1. Use of hazardous chemicals products

The use of hazardous chemical products for Swedish consumption predominantly took place in Sweden and other EU countries (Fig. 2) for the investigated year 2013. The highest scoring individual countries after Sweden were Belgium and Germany, which both have large chemical industries (Cefic, 2018). The highest scoring non-EU country was China (ranked 9th), and thereafter the US (ranked 11th).

Turning to the goods and services with the highest indicator scores for use of hazardous chemicals, the top product group for Swedish consumption was chemicals and pharmaceuticals (Fig. 3). The two following product groups were constructions and dwellings. The constructions product group contains construction of buildings, roads, railroads as well as painting and glass work of finished buildings (Statistics Sweden, 2009). These activities use a number of hazardous chemical products, such as cement, in large volumes (Toller et al., 2013, 2011). The high score for construction in terms of use of hazardous chemicals is in line with previous studies (Palm et al., 2006). The product group called dwellings includes maintenance work of private homes.

There was high use of hazardous substances in Sweden and other EU countries, but it should be noted that the numbers for non-EU countries are likely to be underestimates since conservative estimates were used to extrapolate data to non-EU countries for which original data was missing, as explained in the methods section. It can also be noted that after the two largest product groups, chemical products and constructions, there are many product groups each one corresponding to a smaller share, indicating the widespread use of hazardous chemicals across sectors.

4.2. Use of pesticides

In contrast to the use of other hazardous chemical products, which was found to be predominantly taking place in Sweden and other EU countries (Fig. 2), the use of pesticides embedded in Swedish consumption is high in many non-EU countries (Fig. 4). After Sweden, the producer countries with the highest individual scores were the Netherlands, Brazil, and Spain. The total score of the producer countries in the Latin American region and the African region also represented high pesticide use for Swedish consumption.

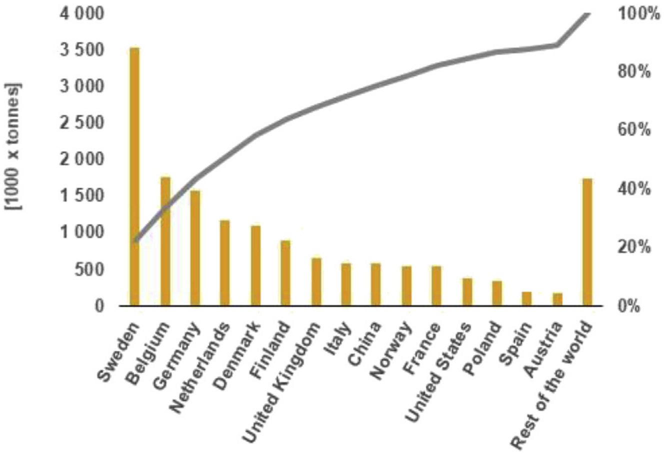

Fig. 2. Use of hazardous chemical products per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

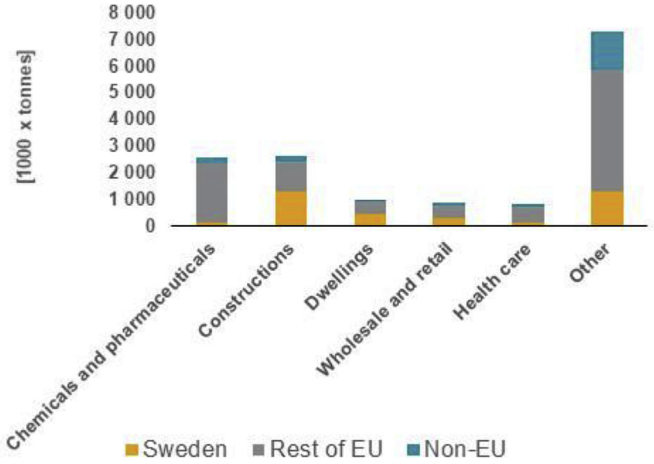

Fig. 3. Use of hazardous chemical products per product group. The results are presented comparing Sweden, the rest of the EU (plus Norway and Iceland) and non-EU.

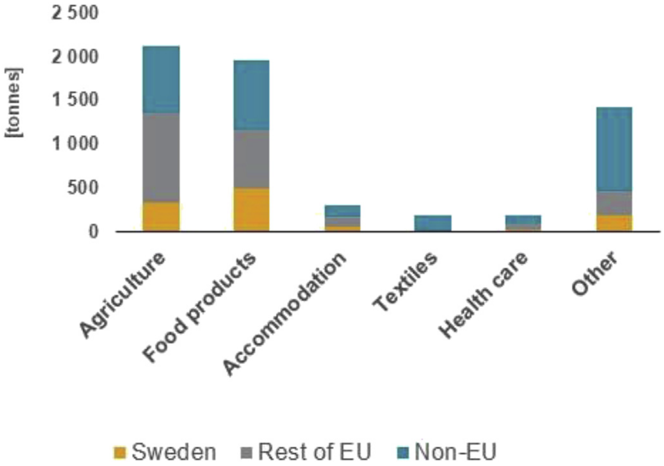

Fig. 5. Use of pesticides per product group. The results are presented comparing Sweden, the rest of the EU (plus Norway and Iceland) and non-EU.

Not surprisingly, the product groups that dominated in use of pesticides were agricultural products and food products (processed) (Fig. 5). On the top 5 list were also accommodation, textiles and health care. Pesticides were used in, for example, the production of textile fibres of agricultural origin. The results for pesticides are presented in further detail for different types of food products in Cederberg et al. (2018).

4.3. Use of antimicrobial veterinary medicine products

Use of antimicrobial veterinary medicine products showed the highest score for Germany with Denmark and Sweden at the second and third place (Fig. 6). This is explained by a relatively high meat import from Germany in combination with the country's high use of veterinary medicine products in livestock production. Germany has more than 10 times higher use of veterinary medicine products per animal population unit than Sweden (EMA, 2016). Swedish agriculture provides domestic consumption with the dominant share of livestock products (e.g. 75% of dairy products, 50% of beef, 70% of pork, 67% of chicken meat) (Swedish Board of Agriculture, 2018) but due to low use of antibiotics in Swedish livestock production, it contributes to only 13% of total use of veterinary medicine products in the overall consumption. Other EU-countries that have very high use of antibiotics are Spain and Italy, and this is reflected in Fig. 6; despite that these two countries are not major export countries of meat and dairy products to Sweden they were still high up on the list of top scores of the indicator. Outside Europe, China and other Asian countries also scored high despite that they are not among the most important exporting countries of animal products to Sweden (Cederberg et al., 2018). This might be a conservative estimate, since we extrapolated data on use of veterinary medicine products in those regions from the average intensity in Europe.

Food products in the form of animal products dominated the total use of VMPs caused by Swedish consumption (Fig. 7). Smaller contributions of mainly indirect flows were found for example in accommodation and health care services which includes served food.

The high level of use of veterinary antimicrobials in imported food feeds into the debate on the risks for antimicrobial resistance. It also points to the lack of consistent data for global veterinary medicine use (see for instance Van Boeckel et al., 2015) and the

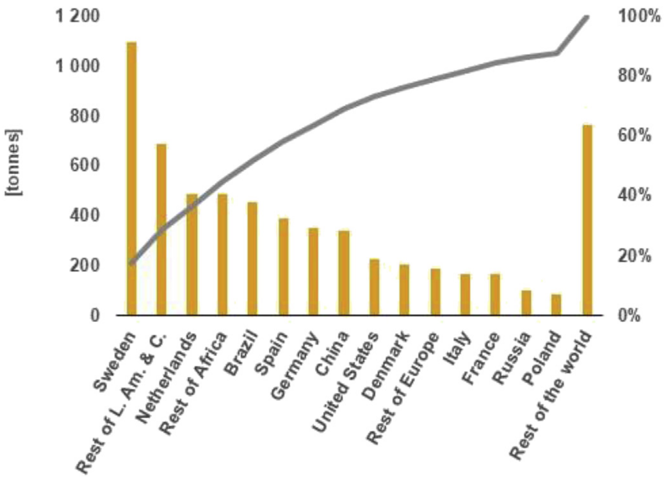

Fig. 4. Use of pesticides per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

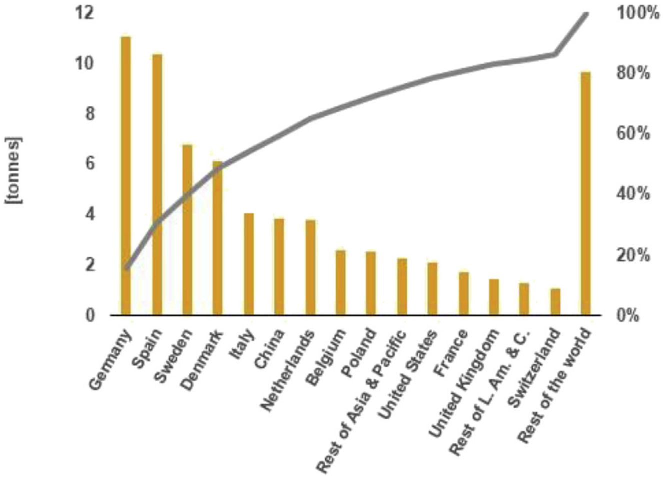

Fig. 6. Use of veterinary medicines per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

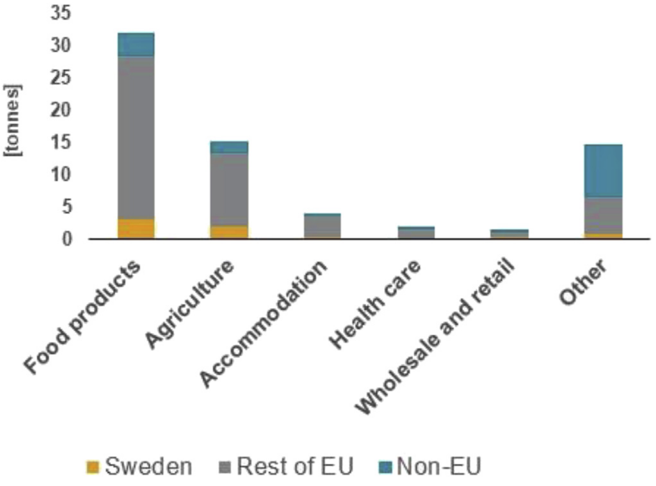

Fig. 7. Use of veterinary medicines per product group. The results are presented comparing Sweden, the rest of the EU (plus Norway and Iceland) and non-EU.

need for better reporting procedures for an efficient monitoring system at the global level. The results for veterinary medicines are presented in further detail for different types of food products in Cederberg et al. (2018).

4.4. Emissions of hazardous chemicals

The indicator on emissions of hazardous substances showed that two countries together carried a high share of the burden of the reported emissions associated with Swedish consumption. These countries were Russia and Sweden (Fig. 8). Thereafter followed China, the United States, and Norway.

In terms of the product groups associated with the highest reported emissions it can be noted that no specific product groups dominated the results. Instead the emissions were spread out over a large number of product groups. The two product groups with highest reported emissions were constructions as well as coke and refined petroleum products. Especially the latter can explain both that the emissions are spread over many product groups, since petroleum products are used in the production of many products and services, and that Russia and Norway were important countries for this indicator, since Sweden is importing high volumes of petroleum products from these countries. In contrast to the use of hazardous chemical products indicator, the emissions indicator showed the highest scores outside of EU borders. The emissions for non-EU countries may, in addition be underestimates, since emissions for countries that have not reported emissions were estimated using a conservative approach.

4.5. Potential impact of hazardous emissions on human health

The potential impact on human health of emissions of hazardous chemicals was highest in Sweden, followed by China, Germany and Russia (Fig. 9). The Asia and Pacific region was also among the top scorers on the indicator.

The share of potential impact of emissions on human health was spread over many different product groups and no specific product group dominated the results. Machinery and equipment (not elsewhere classified) together with constructions and motor vehicles were the highest scoring product groups. However, as noted earlier, there is a risk that the results for non-EU and non-OECD countries are underestimates.

4.6. Potential impact of hazardous emissions on the environment

Potential impact on the environment, represented by the ecotoxicity indicator, showed the same high scoring producer countries as the human toxicity indicator, albeit in a different order (Fig. 10). Germany has replaced China as the second largest after Sweden, and Denmark was on third place.

The share of different product groups differed notably compared to the impact on human health, with warehousing and postal services on top. This product group also contains support services for different types of transports (air, water and road). It should however be noted that the potential impacts are rather evenly spread out over several product groups.

4.7. Results inside vs outside Swedish borders

For all indicators, a comparison between Sweden and rest of the world was made in terms of use and emissions of hazardous substances (Fig. 11). Between 76 and 90% of the use, emissions and potential toxic impact for Swedish consumption took place outside

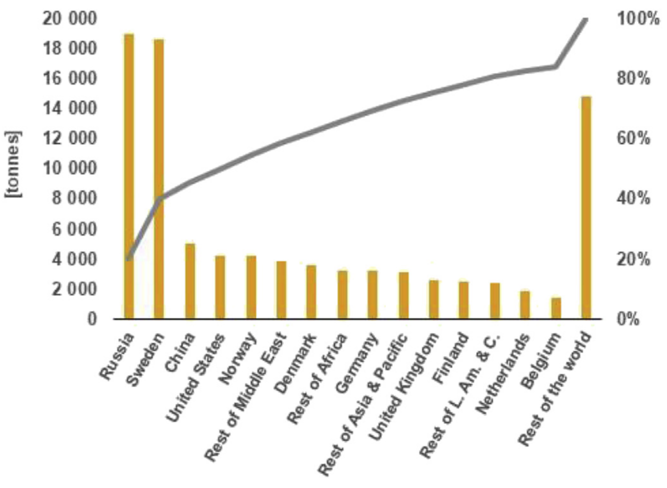

Fig. 8. Emissions of hazardous substances per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

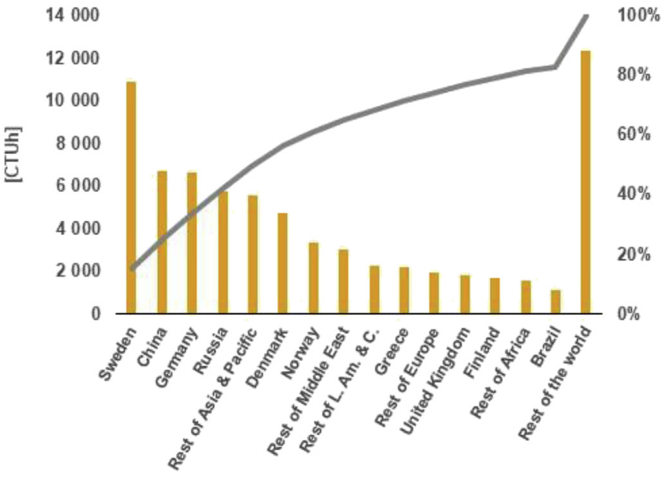

Fig. 9. Potential impact of hazardous emissions on human health, per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

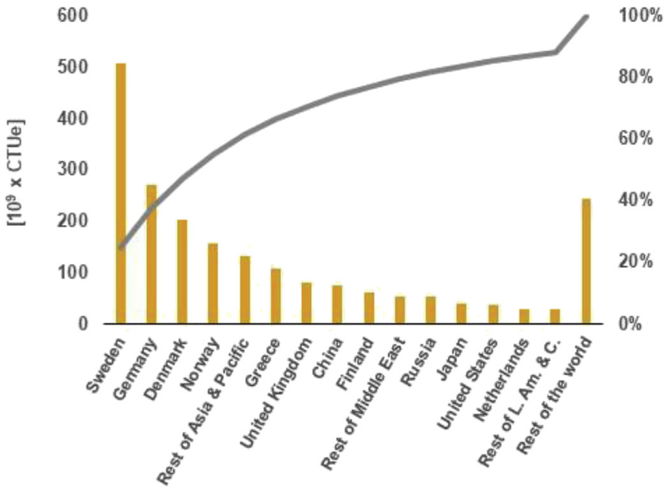

Fig. 10. Potential impact of hazardous emissions on the environment, per producer country (yellow bars). Grey line shows cumulative results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Swedish borders. Use of veterinary antimicrobial medicines was the indicator with the lowest relative value for Sweden and thus the highest relative pressure outside Swedish borders. The indicator results were also compared to the contribution from the associated production to the GDP, which shows that the largest share (76%) of the value added of the production takes place within Swedish borders.

In addition, indicator results for Swedish consumption were compared to the corresponding values for Swedish production (Fig. 12). The use of veterinary medicines and pesticides stand out as having the highest relative difference between the consumption-based and the production-based values, with almost seven and four times larger consumption-based values, respectively. This highlights that a consumption-based approach can show a completely different pattern than what is seen from production-based calculations, supporting the need for the suggested PRINCE indicators.

It is expected that different product groups would be the highest scoring when a consumption or a production-based perspective is used. For example, previous studies have indicated that the metals production as well as pulp and paper industries are important sources for emissions and potential impacts of hazardous chemicals in Sweden from a production perspective (Nordborg et al., 2017; Sörme et al., 2016). These are important Swedish export industries. From a consumption perspective, other product groups come into focus, as shown here.

5. Discussion and conclusions

We conclude that the developed set of indicators has enabled the calculation of consumption-based chemical use and emissions for Sweden. The indicators represent different categories of the DPSIR framework, advancing indication in the areas where existing databases so allow. These indicators are constructed for monitoring consumption pressures primarily at the macro scale – at the level of the whole economy or whole product groups. The results can be used to assess the overall success of broad sustainability efforts, for example the Swedish national environmental objective A Non-Toxic Environment (SEPA, 2017), which in the latest assessment was judged not to be reached with current policy instruments and other measures (SEPA, 2018).

The indicator results have shown that hazardous chemicals are used in, and emitted from, the production of a high number of product groups spread over various sectors of the economy. Construction and food sectors stand out as having high use and emission. These product groups are also important for other types of emissions, such as emissions of greenhouse gases, sulphur dioxide and nitrogen oxides (Fauré et al., 2018). According to the results presented here, the use of hazardous chemical products associated with Swedish consumption is primarily taking place in EU countries including Sweden, whereas the use of pesticides is high in countries outside the EU.

For the indicators on emissions, and the potential toxic impact of these emissions, the most important product groups were construction, petroleum products, machinery and wholesale trade. Notably, when looking at the volumes of emissions with the emissions indicator, construction was the most important product group, whereas when weighted with potential toxic impact, the machinery product group scored higher for the potential human toxicity, and wholesale trade is taking the first place for potential ecotoxicity. This indicates that construction has larger emissions in volume, but the most toxic contribution comes from emissions from other product groups.

With the consumption-based approach of these indicators we can show that the impact of Swedish consumption in terms of use and emissions of hazardous substances for many product groups is to a large extent taking place outside the Swedish borders. Only 10–24% of the chemical pressure from Swedish consumption is occurring within Swedish borders. In the perspective of the Swedish generational goal, this implies that a policy response to reduce risks associated with the use and emission of hazardous substances needs to address both the territorial use and emissions, as well as those in other countries.

For some product groups associated with high use of hazardous chemical products, such as construction, the largest producer countries of Swedish import belong to the EU with its common chemicals management regime called Registration, Evaluation,

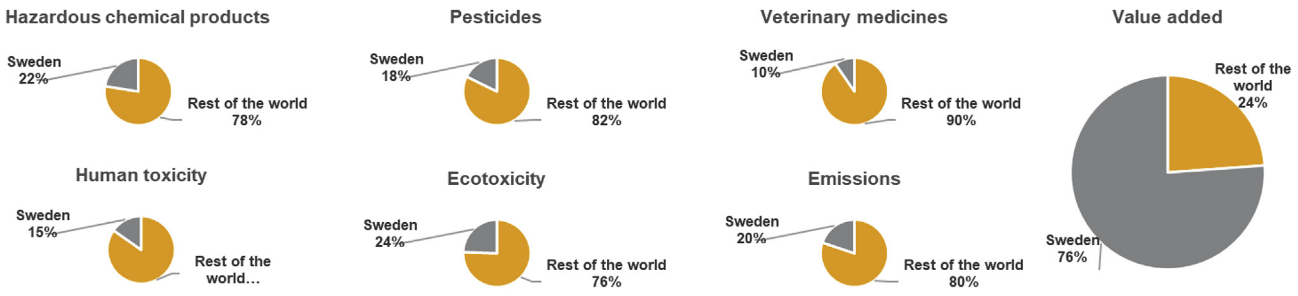

Fig. 11. Share of use, emissions, and potential impact in Sweden vs outside Sweden across all indicators and compared to the share of the consumption as contribution to the Gross Domestic Product (Value added).

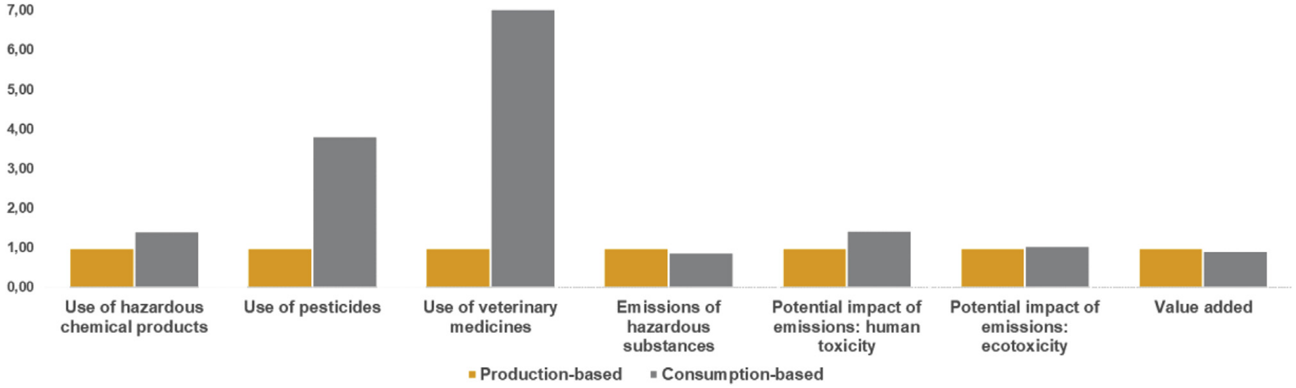

Fig. 12. Consumption-based versus production-based indicators across all indicators (normalized to production-based = 1), including the contribution to the Gross Domestic Product (Value added).

Authorisation and Restriction of CHemicals (REACH, 2006). Outside the EU, there is considerable variety in the level of basic chemicals legislation in countries producing for Swedish consumption (see for instance Persson et al., 2017). It should be noted that in practice, a smaller use of hazardous substances in a producer country with low regulatory level of chemicals management may constitute a significantly higher risk to human health and the environment than a larger use in a more well-regulated and risk reducing setting. In addition to contributing to the development of joint EU regulations aimed at reducing risks with the use of hazardous substances, countries like Sweden which aim to reduce the consumption pressure, may also use for instances bilateral cooperation with producer countries on improved chemicals management as a way to reduce the negative impacts of the imported production (Persson et al., 2015).

The different indicators result in different hotspots in terms of producer countries and regions, as well as product groups, suggesting that the indicators are complementing each other and together provide a more complete picture of chemical pressure. The indicators also feed into the policy debate for different legislative spaces, with the use of hazardous chemical products being regulated primarily through REACH in the EU and is about up-streams decisions on which chemicals to use under which restrictions and conditions. The pesticides and veterinary medicines belong to agricultural policies sphere. And lastly, the emissions indicator with the linked potential impact indicators inform for instance policies on emission controls of large point sources as well as broader efforts towards sustainable material flows in the circular economy through improved production processes.

The calculated indicators are all associated with different types of uncertainties and data-gaps. The indicator for use of hazardous chemical products is based on data for Sweden. This data is considered fairly complete since its collection is regulated by law. However, the extrapolation of Swedish data to other countries creates uncertainties and there is a risk that the results are underestimates especially for countries with weaker chemicals management control. Also, for the use of veterinary medical products, there is a risk of underestimation since the extrapolation was made from European countries to all other countries in the world.

It should be noted that there are significant data gaps in the databases used. For the driver-type indicators, it is likely that they cover most data they intend to cover, although there are data gaps concerning certain countries. For the pressure-related indicators, it is clear that the databases only capture a limited fraction of the emissions of the thousands of chemicals used and produced in society. The lack of data can be illustrated by comparing the number of chemical products included in the data from the Swedish SEEA (close to 100 000) and the number of chemicals (substance groups) included in the E-PRTR (less than 100). This means that the pressure-type indicators will provide less comprehensive results: whereas the indicator on use of hazardous substances includes all the use of the substances of certain classifications, the emission indicators only cover a share of all emissions.

In this paper we have presented indicator results for specific product groups within the Swedish consumption and individual producer countries. It should be noted that the uncertainties increase with increasing disaggregation. When even more disaggregated results are needed, for example for discussing detailed results of specific product groups, other methods, such as life cycle assessment, may be more appropriate. Because of the uncertainties and underestimations in the calculated numbers, the absolute numbers of the results should be treated with caution.

The study presented here has used a specific country as a case for exploring the possibilities for consumption-based macro indicators for chemicals, but the model could be applied also to other countries. Similar calculations for more countries would serve to inform not only different national environmental objectives but also the efforts on the chemical related targets under the global 2030 Agenda.

An important next step of the research presented here is to develop time series of the indicators. Other improvements would include further investigation and reduction of uncertainties in the extrapolations of data discussed above. This would include adding more data on emissions of hazardous chemicals, testing other characterization methods for calculating potential impacts, as well as developing and testing other methods for extrapolation of data on use and emissions of hazardous chemicals and chemical products to countries where data is lacking.

A continued discussion on how to follow the flows of hazardous chemicals in society is needed. The indicators suggested here are intended to inspire additional discussion in the academic field as well as in the policy sphere on effective ways of monitoring chemicals and the risks associated with their use and emissions. In addition to the indicators presented here, further work is also needed in the response category, in order to achieve effective chemical risk reduction and sound chemicals management across countries and regions. Furthering this discussion will be useful for many processes, including the Strategic Approach to International Chemicals Management framework and the targets on chemicals management included in the Sustainable Development Goals. Other current discussions that are closely related to the chemicals indicator development is the work on chemical footprints (Bjørn et al., 2014; Rydberg et al., 2014; Sala and Goralczyk, 2013; Sörme et al., 2016), the planetary boundary of chemical pollution (Diamond et al., 2015; MacLeod et al., 2014; Persson et al., 2013; Steffen et al., 2015), and the development of normalization data for life cycle impact assessment (Cucurachi et al., 2014; Pizzol et al., 2016). A common feature for all these discussions is the need for comprehensive databases for the use and emissions of chemicals. As has been shown in this paper, there is a need for further development of such databases.

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Appendix A–D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.12.294.

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