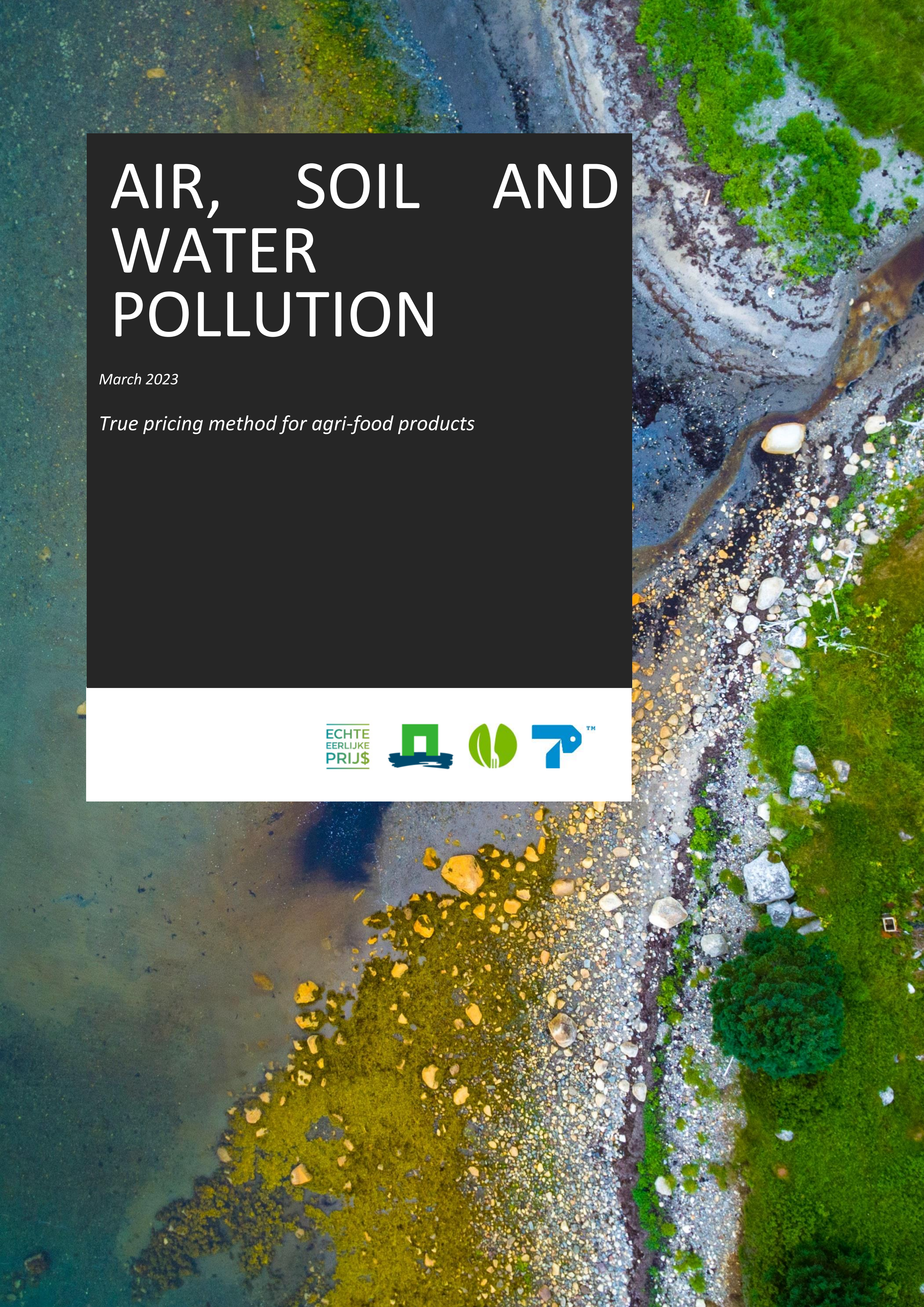

AIR, SOIL AND WATER POLLUTION

March 2023

True pricing method for agri-food products

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Air, soil and water pollution

Impact-specific module for true price assessment

True pricing method for agri-food products

Version 2, March 2023

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Deze rapportage maakt deel uit van de PPS AF18051/ TU18104 'Echte en Eerlijke Prijs voor Duurzame Producten'[4].

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[4] For more information on the *PPS True and Fair Price for Sustainable Products*, please refer to https://www.wur.nl/nl/project/Echte-en-eerlijke-prijs-voor-duurzame-producten.htm

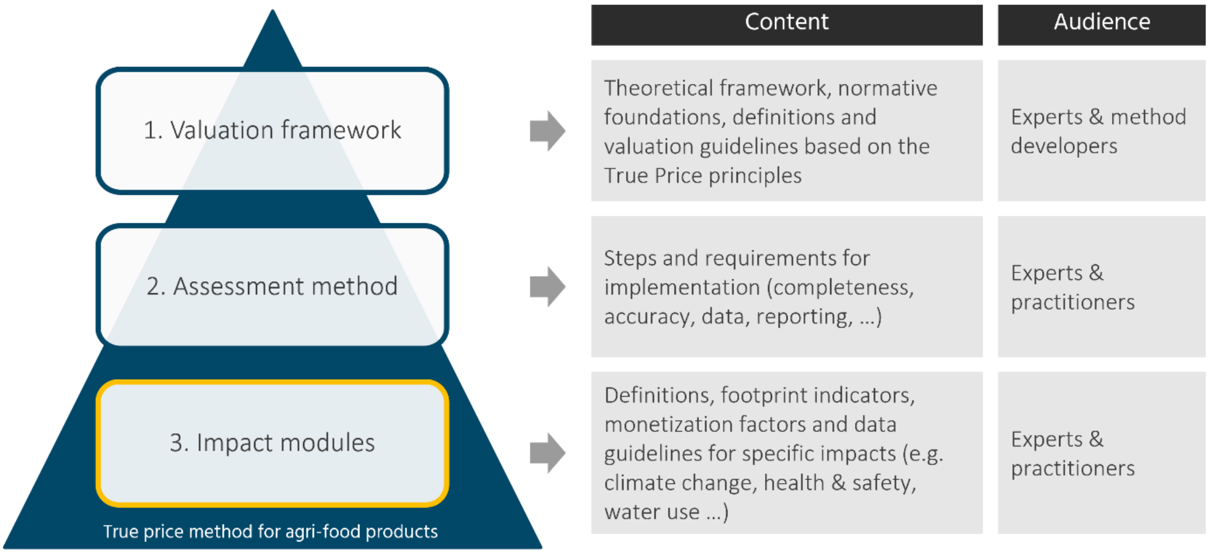
Relation to other components of the true price methodology for agri-food products

*This **Air, soil and water pollution - Impact-specific module for true price assessment** was developed by True Price and Wageningen Economic Research within the PPS True and Fair Price for Sustainable Products.*

This document contains the key methodological aspects to measure and value three impact categories of agri-food products and value chains: air, soil and water pollution.

*This impact-specific module is complemented by five other **Natural capital modules** and seven **Social and human capital modules**. The other natural capital modules are: 1) Contribution to climate change; 2) Soil degradation; 3) Land use, land use change, biodiversity and ecosystem services; 4) Scarce water use; 5) Fossil fuel and other non-renewable material depletion. These impact-specific modules are preceded by the **Valuation framework for true pricing of agri-food products**, which contains the theoretical framework, normative foundations and valuation guidelines, and the **Assessment Method for True Pricing of Agri-Food products**, which contains modelling guidance and requirements for scoping, data and reporting (Figure 1).*

Together, these documents present a method that can be used for true pricing of agri-food products, and potentially other products as well.



Content	Audience
Theoretical framework, normative foundations, definitions and valuation guidelines based on the True Price principles	Experts & method developers
Steps and requirements for implementation (completeness, accuracy, data, reporting, …)	Experts & practitioners
Definitions, footprint indicators, monetization factors and data guidelines for specific impacts (e.g. climate change, health & safety, water use …)	Experts & practitioners

Figure 1: Components of the true price methodology for agri-food products. This document is one of the impact modules.

Overview of changes between versions

This document is an updated version of the Air, Soil and Water pollution module, originally published in November 2021. In short, the main change is that the practitioner now has a choice between two method options:

1. An option that assesses a product's pollution impact based on average global effects (presented in the main text)
2. An option that accounts for regional effects of pollution (presented in the annexes)

An overview of the changes made to the 2021 version is provided in the table below. These changes were necessary because a misinterpretation of characterisation factors resulted in double counting of regional effects when country-specific monetisation factors were applied. Therefore, the previous method to account for the region-specific effects of PM, POF and acidification should not be used anymore. The methods for other indicators were not affected and remain unchanged. A more detailed explanation is provided in the next paragraphs.

Error in previous version

The previous method provided a similar approach to account for either the global or the regional effects of photochemical oxidant formation (POF), particulate matter (PM) and acidification. This approach was based on impact characterisation of three indicators at midpoint level: POF (expressed in kg NO_x-eq), PM (expressed in kg $PM_{2.5}$-eq) and acidification (expressed in kg SO_2-eq). The valuation approach (i.e., the monetisation) for these three indicators relied on their conversion from midpoint to endpoint (damage to human health and/or ecosystems). In the previous version, it was wrongly assumed that the required conversion factors for individual countries were provided in ReCiPe 2016 (Huijbregts et al., 2017). However, only a conversion factor (from midpoint to endpoint) for average global effects was provided. For region-specific effects, endpoint characterisation factors for specific pollutants (NH_3, NO_x, $PM_{2.5}$, SO_2, NMVOC), rather than the midpoint indicators (PM, POF and acidification), were provided. As a result, impact characterisation of pollutants was included twice, once at midpoint level and once at endpoint level, potentially leading to double counting of effects.

Solution in current version

Annex H was added to the latest version of the module and replaces the previous method to account for three regional effects of air pollution: POF, PM and acidification. It does not include double counting, as the current version only includes endpoint characterisation once, in the valuation approach.

Unchanged between previous and current version

In general, for all impacts, the method accounting for average global effects did not change. Therefore, the global monetisation factors also did not change for any of the indicators. No method to account for regional effects of toxicity and ozone layer depletion is provided. Therefore, no changes were made for the relevant indicators (toxic emissions to air, soil and water, and ozone layer depleting emissions).

The valuation of eutrophication and nitrogen deposition does not depend on ReCiPe characterisation factors, so the error described above did not apply to the three relevant indicators (freshwater and marine eutrophication and nitrogen deposition). For these indicators, the option to account for region-specific effects remained unchanged. Annex D covers eutrophication and Annex F.2 covers nitrogen deposition.

Change	**Brief explanation**
Removed method to assess region-specific pollution effects of particulate matter formation (PM), acidification and photochemical oxidant formation (POF) from the main text	Compared to the 2021 version, no method is provided anymore to assess region-specific effects of PM, POF and acidification using ReCiPe midpoint characterization factors (PM, POF and acidification). See explanation below table and alternative provided in row below.
Added method (using different indicators) to include region-specific pollution effects of PM, POF and acidification in Annex H	The PM, POF and acidification indicators are replaced by five new indicators to account for regional effects of PM, POF and acidification. The new indicators are: $PM_{2.5}$ emissions to air, NH_3 emissions to air, SO_2 emissions to air, NO_x emissions to air and NMVOC emissions to air.
New indicators for POF	The midpoint indicator of POF is now split into the two different endpoint effects connected to: ecosystems damage and damage to human health.
Removed POF indicator expressed in kg NMVOC-eq	Following from the point above, the new disaggregated indicators are modelled and quantified only in kg NO_x equivalents.

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1. Introduction

This document provides a method module for the assessment of the true price of an agricultural or horticultural product, within the public-private partnership ‘Echte en Eerlijke Prijs’. It contains the key methodological aspects to measure and value three categories of impacts of agri-food products and value chains: air, soil and water pollution.

This module must be used together with the **True Pricing Assessment Method for Agri-food Products** (Galgani et al., 2021a). As for other impacts in true pricing, this methodology is compatible with Life Cycle Assessment (LCA).

Throughout this document, textboxes like this outline the structure of the following sections. They provide pointers to readers looking for specific information.

- Section 2 provides the key definitions.
- Section 3 provides background information and the rationale for including these impacts as part of the true price.
- Section 4 offers guidance for scoping and determining materiality within a true price assessment.
- Section 5 presents the footprint indicators of the impacts.
- Section 6 the modelling approach per impact.
- Section 7 provides the monetisation approach.
- Section 8 provides an overview of limitations and key items for further research.
- Annexes with additional information are provided at the end of the document. Annex H provides an alternative method to the one presented in the main body of text to capture regional effects of three air pollution indicators (PM, POF and acidification). The method can be followed to obtain country-specific monetisation factors for all regions included in Recipe 2016. In this module, it has been applied to obtain Dutch and global factors.

2. Definitions

Air, soil and water pollution are environmental impact categories of processes related to agri-food production and consumption and are defined as follows:

- **Air pollution** is defined as the impacts caused by emissions to air other than climate change, including acidification, photochemical oxidant formation, particulate matter formation, nitrogen deposition from emissions to air, ozone layer depletion, terrestrial and aquatic ecotoxicity and human toxicity from toxic emissions to air. Pollutants related to the first four impacts are sulphur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), ammonia (NH_3), nitrogen oxides (NO_x) and Non Methane Volatile Organic Compounds (NMVOC). An extensive number of pollutants contributes to ozone layer depletion, ecotoxicity and human toxicity.
- **Soil pollution** is defined as eco- and human toxicity caused by emissions to soil or crops. It occurs due to the runoff and discharge of contaminants, for example heavy metals and pesticides.
- **Water pollution** is defined as emissions to water contributing to ecotoxicity and human toxicity, as well as eutrophication of marine- and freshwater. Eutrophication occurs due to the runoff and discharge of nutrients, for example from leaching of plant nutrients into soil, marine and freshwater bodies and the subsequent rise in nutrient levels, i.e., of Phosphorus (P) and Nitrogen (N).

Pollution impacts as commonly defined in LCA methods are here grouped in three main categories: air pollution, soil pollution and water pollution. Using these three categories is a simplification, as air pollution, water pollution and soil pollution are intrinsically related. Emissions of pollutants to each of these compartments (air, soil and water) have effects on the other ones as well, based on environmental transport of pollutants and environmental cause-effect relations. Therefore, for example, emissions to air can lead to effects on water quality. In this method, the categories are derived based on the emission compartment, i.e., where emissions take place, rather than where effects occur. So, all emissions to air fall under air pollution, and the same holds for emissions to soil (soil pollution) and water (water pollution). Use of pesticides falls under soil pollution.

As a result, air pollution includes not only effects on air quality such as ozone layer depletion, photochemical oxidant formation and particulate matter formation, but also terrestrial-, freshwater- and marine ecotoxicity, nitrogen deposition and terrestrial acidification due to emissions to air. Soil pollution includes freshwater and marine ecotoxicity due to emissions to soil and water pollution includes terrestrial ecotoxicity. Furthermore, air, soil and water pollution all include effects on human toxicity.[5]

There are alternatives to this categorisation (e.g., categorising based on where effects occur); what is important, irrespective of the chosen categorisation, is to clearly capture all effects that occur, while preventing possible double counting between impacts. Classifying air, soil and water pollution impacts based on the emission compartment is preferred as it provides information on impact that is easier for businesses and farmers to use and interpret to manage their impact. Businesses and farmers often have available information on the emission compartment of their emissions, rather than the environmental compartment where the effects occur. For example, business typically have control on their emissions to air, soil and water. These are also grouped in the context of a true price assessment under air, soil and water pollution accordingly.

3. Background and rationale for including these impacts as part of the true price

Pollution occurs through different types of emissions to air, water and soil that lead to various types of deterioration of the natural environment or of human health.

The indicators considered under air, soil and water pollution are commonly included among environmental impacts for products in LCA (Frischknecht & Jolliet, 2016). They also constitute negative externalities of production that should be accounted for in true pricing based on the **Valuation Framework for True Price Assessment of Agri-food products** (Galgani et al. 2021b), which takes internationally accepted agreements on the rights of current and future generations as a starting point.

The inclusion of air, soil and water pollution among the impacts in scope for true pricing is linked to several rights: *the right to a safe, clean, healthy and sustainable environment*, *the right to a safe and clean drinking water*, as well as to *the right of everyone to the enjoyment of the highest attainable standard of physical health*.[6]

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[5] Note that pesticide application is considered under soil pollution.

[6] For more information, see

Annex A: Link with internationally accepted agreements on the rights of current and future generations, in this document, and the Valuation Framework for True Price Assessment of Agri-food Products (Galgani et al. 2021b).

An air pollution sub-indicator that warrants special attention is nitrogen deposition. Nitrogen deposition[7] due to Nitrogen emissions is an acute problem in the Netherlands, and emissions of Nitrogen in nature areas in other European countries can also be problematic. The EU has set limits for deposition of Nitrogen in protected areas (so-called Natura 2000 areas). If nitrogen deposition happens in nature-sensitive areas, this can give rise to unacceptable biodiversity loss. The Dutch high court (Raad van State) ruled in 2019 that insufficient protection of the nature areas is incompatible with European legislation (Raad van State, 2019). As a result, the then-leading national Nitrogen policy 'Programma Aanpak Stikstof' could no longer be used as basis for allowing activities such as agriculture and construction that potentially lead to nitrogen deposition in sensitive nature areas (van den Born et al., 2020). The most important sources of deposition of Nitrogen in Nature 2000 areas are emissions to air of ammonia (NH_3) and nitrogen oxide (NO_x).

Based on the above, in true pricing we consider economic actors to have a responsibility to limit their contribution to air, soil and water pollution. This includes cases in which businesses already comply with the legal requirements set for emissions in a given context, since every gram of pollutant emitted still has marginal negative effects for the environment and human health. This is in line with LCA methodologies[8] and the definition of external costs which considers any unwanted effect, and therefore all emissions of pollutants, as externalities (de Bruyn et al., 2018a; Bickel & Friedrich, 2005). However, it would be worthwhile to explore whether it would be possible to determine a level of 'zero harm' emissions per product, and then only include emissions beyond this boundary in the true price gap. This could be based, for example, on planetary or local biophysical boundaries (Robèrt et al., 2013). This approach would be in line with the rights-based approach of true pricing, although challenging.

4. Guidance for the scoping phase within a true price assessment

In a typical scoping phase of a true price assessment, the researcher should identify all relevant processes in the life cycle of the product (or steps in its value chain). This involves assessing which intermediate products are produced and what inputs are required. After that, it should be determined which impact must be quantified for each process in the life cycle – a so-called materiality assessment - by identifying all relevant processes that are expected to contribute more significantly to the total impact. This helps the analysis as it focusses attention on these processes in subsequent steps. This process should be done following the steps and requirements laid out in the **True Pricing Assessment Method for Agri-food Products** (Galgani et al, 2021a).

Most agricultural supply chains involve emissions to air/soil/water. These emissions are caused, for example, by the production and application of fertilisers and pesticides, by the management of manure and by all processes that require energy (electricity and fossil fuels). Processes such as food-processing, transport, logistics, manufacturing of packaging and waste management are also typically linked to air and water pollution. The following rules of thumb can be used:

- All agricultural processes that require the use of organic or synthetic fertilisers are material for water pollution.
- All agricultural processes that require the use of pesticides (herbicides, insecticides, fungicides, rodenticides) are material for soil pollution.
- All processes that require significant amounts of fuel or electricity are potentially material for air pollution.

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[7] Also known as terrestrial eutrophication.

[8] In a Life Cycle Inventory, all emissions are accounted for. This is the standard LCA approach, see for example the Product Environmental Footprint Guide (PEF) of the European Commission (EC, 2013).

- In an agricultural context, emissions of NH_3 are typically associated with holding cattle, pigs and poultry in stables, and with storage and application of manure to fields.
- All processes that lead to wastewater are material for water pollution, regardless of the degree to which wastewater is treated (this will be reflected in the data and in the results).
- Livestock is always material for air and water pollution.

For all other processes, it is advised to use existing LCA studies for comparable products or a broadly accepted method to determine the materiality of specific indicators for the steps in the life cycle of the product under study. An example is the Product Environmental Footprint Category Rules (PEFCR) of the European Commission, which are available for selected agricultural products[9]. If no further guidance is available, research is required to determine which stages of the life cycle are material for air, soil and water pollution respectively.

5. Footprint indicators

Figure 2 provides an overview of the footprint indicators. Indicators are categorised based on the compartment (air, soil or water) that the relevant pollutants are emitted to (following Section 2). Each (sub)indicator is expressed in a specific unit, depending on the method used to quantify its effect.

Most pollution impacts are quantified in line with LCA methods and follow the ReCiPe Life Cycle Impact Assessment Methodology midpoint indicators (Huijbregts et al., 2017). Exceptions are the quantification of human toxicity (ReCiPe endpoint quantification for human health, measured in Disability-Adjusted Life Years (DALY)[10] and nitrogen deposition.

Regional accuracy of impact measurement

The list of indicators in Figure 2, as well as the modelling approach and monetisation factors in the main body of text, present one approach to include three air pollution impacts (particulate matter formation, photochemical oxidant formation and acidification) in a true price assessment. This approach can be used in certain situations: 1) in case of a general estimation that does not require accounting for regional effects, 2) when data availability is limited and only secondary data on LCA midpoint results are available.[11]

If the goal and scope of the assessment require a higher level of regional accuracy, Annex H provides the method to account for the regional effects of these three impacts. This approach requires data on pollutant rather than midpoint level and is recommended when these data points are available. Text boxes similar to this one can be found throughout the main body of the text, referring to the region-specific method for particulate matter formation, photochemical oxidant formation and acidification.

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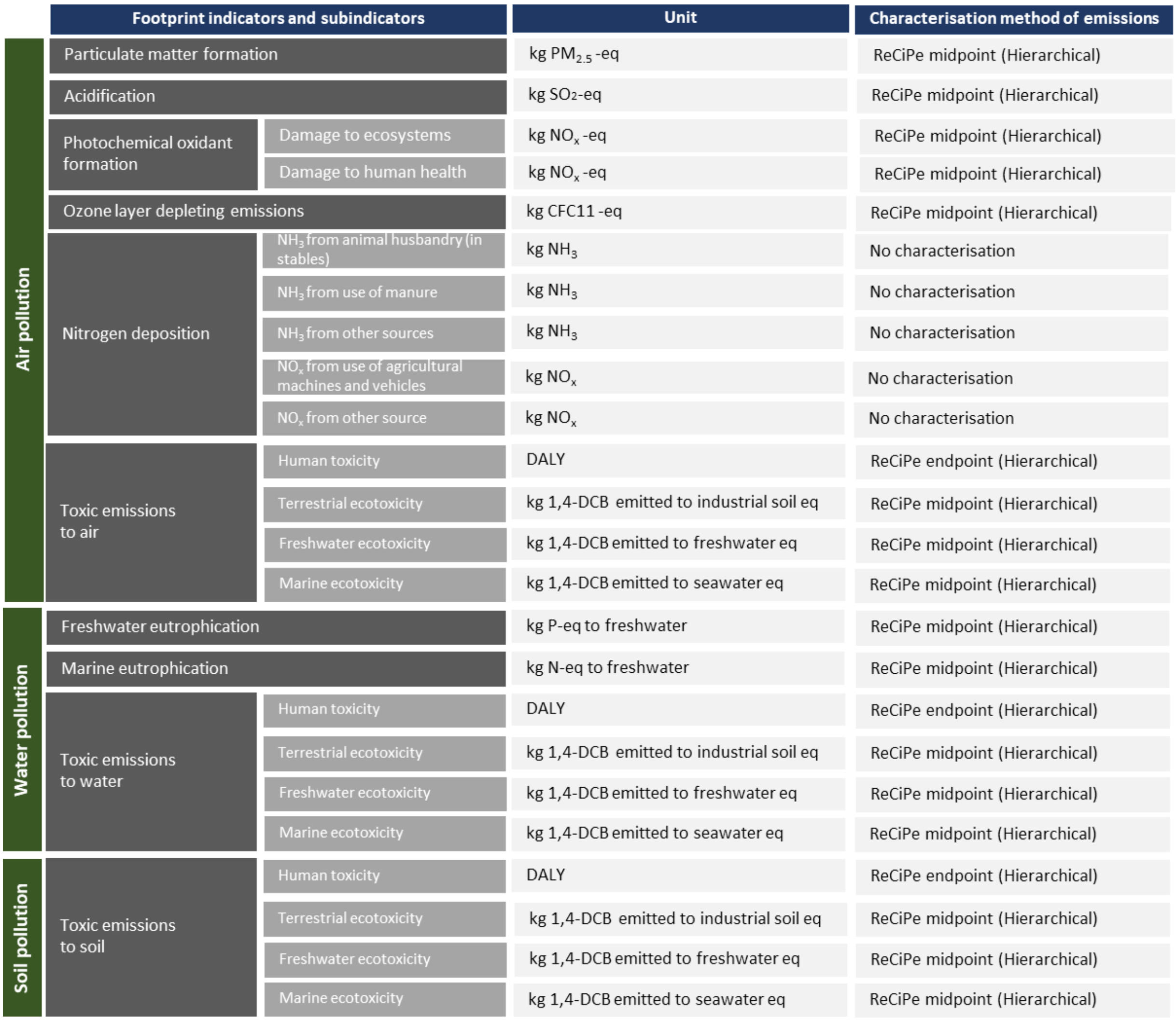
[9] See the Product Environmental Footprint Pilots by the European Commission available at https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm.

[10] DALY is a unit of health which represents one year of life in good health. DALYs reflect the negative effects of illnesses and accidents on lifespan and quality of life and can therefore be used to measure the impacts of pollution on people. The DALY load of a disease is the sum of Years of Life Lost (YLL) and Years Lost due to Disability (YLD) (WHO, 2019a).

[11] Midpoint results should align with the Recipe methodology described in Huijbregts et al. (2017).



	Footprint indicators and subindicators		Unit	Characterisation method of emissions
Air pollution	Particulate matter formation		kg $PM_{2.5}$-eq	ReCiPe midpoint (Hierarchical)
	Acidification		kg SO_2-eq	ReCiPe midpoint (Hierarchical)
	Photochemical oxidant formation	Damage to ecosystems	kg NO_x-eq	ReCiPe midpoint (Hierarchical)
		Damage to human health	kg NO_x-eq	ReCiPe midpoint (Hierarchical)
	Ozone layer depleting emissions		kg CFC11-eq	ReCiPe midpoint (Hierarchical)
	Nitrogen deposition	NH_3 from animal husbandry (in stables)	kg NH_3	No characterisation
		NH_3 from use of manure	kg NH_3	No characterisation
		NH_3 from other sources	kg NH_3	No characterisation
		NO_x from use of agricultural machines and vehicles	kg NO_x	No characterisation
		NO_x from other source	kg NO_x	No characterisation
	Toxic emissions to air	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)
Water pollution	Freshwater eutrophication		kg P-eq to freshwater	ReCiPe midpoint (Hierarchical)
	Marine eutrophication		kg N-eq to freshwater	ReCiPe midpoint (Hierarchical)
	Toxic emissions to water	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)
Soil pollution	Toxic emissions to soil	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)

Figure 2: Overview of footprint indicators and sub-indicators per impact.

Air pollution consists of six footprint indicators: toxic emissions to air, particulate matter formation, photochemical oxidant formation, acidification, ozone layer depletion and nitrogen deposition. Toxic emissions to air consists of four sub-indicators: terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and human toxicity. The same footprint indicators apply to toxic emissions to soil and water. Photochemical oxidant formation consists of two sub-indicators: damage to ecosystems and damage to human health. Nitrogen deposition consists of two sub-indicators: emissions of NH_3 and emissions of NO_x.

- **Toxic emissions to air** measures the emission of toxic chemicals to air. The emission of these chemicals leads to an increase in human intake and thereby increases the damage to human health. Similarly, the emission of chemicals leads to the increase in species exposure to those chemicals and in potentially disappeared fractions of species, which in turn results in damage to associated ecosystems (Huijbregts et al., 2017).
- **Particulate Matter (PM) formation** consists of: (i) primary aerosols[12] and (ii) secondary $PM_{2.5}$ aerosols that are formed in air from emissions of sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen

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[12] A fine particulate matter with a diameter of less than 2.5 µm ($PM_{2.5}$) representing a complex mixture of organic and inorganic substances.

oxides (NO_x), among other elements (WHO, 2003). It causes human health problems as it reaches the upper part of the airways and lungs when inhaled (Huijbregts et al., 2017).

- **Photochemical oxidant formation (POF)**, or smog formation, is the formation of ozone as a result of photochemical reactions of NO_x and Non-Methane Volatile Organic Compounds (NMVOCs). Ozone is not directly emitted to the atmosphere but it is a health hazard to humans because it can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of respiratory distress in humans, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD). Additionally, ozone can have a negative impact on vegetation, including a reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors (Huijbregts et al., 2017).
- **Acidification** is a consequence of the emission to air of acidifying pollutants. This leads to acid precipitation which increases the level of acidity in the soil, which will cause shifts in a species occurrence (Huijbregts et al., 2017). Acidification is mainly linked to the emissions of NO_x, NH_3, or SO_2 to the air (Van Zelm et al., 2015).
- **Ozone layer depleting emissions** lead to damage to the stratospheric ozone layer resulting in increased UVB-radiation on the Earth's surface. This leads to increased risk of skin cancer and cataract risks. (Huijbregts et al., 2017).
- **Nitrogen deposition,** or terrestrial eutrophication, is the process of deposition of nutrients to soil from gas emissions that leads to an imbalance of thriving species. Nettle, thistles and blackberry bushes will thrive more than other species and take up most available space. In the Netherlands, Nitrogen is the limiting nutrient that can give rise to this imbalance. The most important sources of deposition of Nitrogen in Natura 2000 areas are emissions to air of NH_3 and NO_x (RIVM, 2019).

Soil pollution is calculated as:

- **Toxic emissions to soil**, including the same sub-indicators with toxic emissions to air, but only for toxic pollutants that are emitted to soil or crops. The use of pesticides (herbicides, fungicides, rodenticides, insecticides, etc) in agriculture falls under toxic emissions to soil.

Water pollution is calculated as the sum of three footprint indicators, namely toxic emissions to water, freshwater eutrophication and marine eutrophication.

- **Toxic emissions to water** include the same sub-indicators with toxic emissions to air and soil, but only for toxic pollutants that are directly emitted to water.
- **Freshwater eutrophication** measures the rise in nutrient levels in freshwater bodies due to the discharge of pollutants into water and leaching from soil, including leaching of excess fertilisers. This rise in nutrient levels ultimately leads to algal blooms, which lead to lower water quality, potential damage to human health, loss of species and damage to freshwater ecosystems. Phosphorous is considered the main cause of freshwater eutrophication. (Huijbregts et al., 2017).
- **Marine eutrophication** occurs due to the runoff and leach of plant nutrients from soil and the discharge of those into marine systems. This leads to a rise in nutrient levels in coastal waters. Similar to freshwater eutrophication, the rise in nutrient levels leads to algal blooms, with subsequent damage to health, loss of species and damage to marine ecosystems. Nitrogen is considered the main cause of marine eutrophication (Huijbregts et al., 2017).

5.1. Correspondence with ReCiPe

ReCiPe offers factors for three perspectives (individualist, hierarchist and egalitarian) depending on the value choices done in modelling.[13] It is recommended to use the hierarchist perspective, which is based on scientific consensus.

Regarding units, the ReCiPe methodology (Huijbregts et al., 2017) midpoint indicators are used directly, with some exceptions:

- For human toxicity, the endpoint indicator unit is preferred (DALY instead of kg 1,4 DCB-eq). A midpoint to endpoint conversion factor is given in Annex B. Additionally, human toxicity in ReCiPe is split between carcinogenic and non-carcinogenic. These two indicators can be summed for the purpose of true pricing, as the same monetisation factors is used.
- Ozone depletion is called *Stratospheric ozone depletion* in some versions of ReCiPe.
- Photochemical Oxidant Formation is called *Photochemical ozone formation* in some versions of ReCiPe.
- Nitrogen deposition, for which emissions of NH_3 and NO_x are set as indicators, is not included as an impact in the ReCiPe methodology. Sub-indicators are specified based on the process that leads to their emission. Equal emission volumes through different processes can have different effects on nitrogen deposition (Van der Maas, 2020).
- For terrestrial, marine and freshwater ecotoxicity, a split between toxic emissions to air, soil and water is not part of standard ReCiPe midpoint results from LCA databases. This split can be introduced by looking in isolation at the impacts of the various polluting substances emitted to each of the three compartments (to air, soil, or water). These can also be derived from the Lifecycle Inventory. In cases where this is not possible, ad hoc adjustments to the classification of indicators between air, soil and water pollution might be necessary, or one may decide to present toxicity as a separate compartment next to soil, air and water.

5.2. Correspondence with PEF

The correspondence between environmental impacts in this method and the European Commission's Product Environmental Footprint (PEF) methodology is presented elsewhere, in the **Assessment Method for True pricing of Agri-food Products** (Galgani et al, 2021a, Annex I), as it does not only cover pollution but also other impacts**.**

True price pollution indicators directly correspond to the following four PEF impact categories: Ozone depletion, Particulate Matter/Respiratory inorganics, Photochemical Ozone Formation, Eutrophication – aquatic.

Additionally, the following PEF impact categories are compatible with true price indicators, meaning that the results can be made comparable if equivalence factors between ReCiPe and PEF are known: Acidification, Ecotoxicity for aquatic freshwater, Human Toxicity – cancer effects and Human Toxicity – non cancer effects.

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[13] '*The individualistic perspective is based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation. The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms. The egalitarian perspective is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available.*' (Huijbregts et al. 2017)

Nitrogen deposition in the true price method corresponds to Eutrophication – terrestrial in the PEF method, but equivalence should be done with care since the PEF factors are already used in true pricing to derive country-specific monetisation factors.

Only one PEF impact category is not covered by this method: Ionizing radiation – human health effects. However, it is an outcome of the ReCiPe2016 method, and when one wishes it can be valued with the same approach used to value pollution impacts, based on the midpoint to endpoint factor and the price of a DALY (the resulting monetisation factor is provided in Section 7.1.1).

Finally, two indicators in true pricing are additional to the indicators present in PEF: freshwater ecotoxicity and marine ecotoxicity.

6. Modelling approach

The generic formula for quantifying air, soil and water pollution indicators (except nitrogen deposition) for one specific process in the life cycle of the studied product is presented below (formula 1).

$$I = \sum_{c,p} e_{c,p} CF_{c,p} \tag{1}$$

Where I is a footprint indicator in the unit specified in Chapter 5 (Figure 2); $e_{c,p}$ is the emissions in kg of pollutant p to compartment c (air, soil or water) and $CF_{c,p}$ (in unit footprint indicator/kg) is a global midpoint characterisation factor representing how much an emission $e_{c,p}$ contributes to I. Characterisation factors are available in the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017).

In practice, this approach has three steps:

1) Quantify all emissions of polluting compounds to air, soil and water; after this step, all the emissions are listed and quantified in kg. This corresponds to the life cycle inventory (LCI) in LCA.
2) Multiply each by a set of factors that indicates the contribution of that pollutant to the relevant footprint indicators (e.g., 1 kg of NO_x to air corresponds to 0.11 kg $PM_{2.5}$-eq for PM formation, 0.36 kg SO_2-eq for Acidification, 1 kg of NO_x-eq for photochemical oxidant formation).[14] After this step, all emissions that contribute to one impact are expressed in the unit of the footprint indicator. In LCA this is called characterisation and the factors used are called characterisation factors.
3) Quantify each footprint indicator, by summing all pollutants that contribute to that indicator. In LCA this and the previous step together are called life cycle impact assessment (LCIA).

The emissions in kg of pollutant (*e* in formula 1) can be quantified following LCA (as described above)When this is not possible, it can be estimated by using factors that represent emissions per unit of input used (e.g., agro-chemicals (fertilisers and pesticides), fuel and electricity, and more), of transportation distances and of waste produced in the process under study. For example, factors estimating the NH_3 emissions per unit of fertiliser that is used may be applied. These factors are often available in environmental impact assessment tools, in environmental standards and in scientific literature. It is also possible that data on the impact indicators (I in formula 1) are already available in existing LCA studies. It is then possible to use that directly and therefore simplify the modelling.

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[14] Values correspond to world average potentials from Huijbregts et al. (2017).

Characterisation factors are available in the ReCiPe database and an overview is given in Annex B: ReCiPe characterisation factors for modelling of air pollution.

- The rest of this section describes the approach for all indicators in more detail.
- Additionally, Section 6.6 illustrates the approach for nitrogen deposition and Section 6.7 on aquatic eutrophication provides some guidance on how to estimate leaching of nutrients to water bodies.
- Readers that are familiar with the use of LCIA methods such as ReCiPe can skip to 6.6 and 6.7.

6.1. Toxic emissions to air, soil and water

An inventory of emissions of toxic compounds to the environment in the various processes of the product life cycle should be prepared. The quantity of toxic compounds emitted to air/soil/water in kg/unit is then multiplied with the characterisation factors from the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017) to quantify human and eco-toxicity. All sub-indicators are then summed.

The toxicity method has been reviewed in light of state-of-the-art LCA standards such as the UNEP SETAC Life Cycle Initiative and EU’s Product Environmental Footprint (PEF). The UNEP SETAC LCI has developed the USEtox method, which is also adopted by PEF in a modified version. USEtox is an important quantification method, but for the time being ReCiPe is adopted for the true price method, as it has a broader coverage of indicators when it comes to ecotoxicity. ReCiPe is also well-accepted in the LCA community and it does build on USEtox. More information on the choice of ReCiPe to quantify toxicity can be found in Annex C: Comparison between ReCiPe and USEtox methods for quantifying toxicity. It is recommended to review this choice in the coming years, with the involvement of toxicity experts.

The characterisation factors of human toxicity are expressed in DALY loss per kg of pollutant (endpoint), while the ones for terrestrial ecotoxicity in kg 1,4-DCB emitted to industrial soil equivalent per kg of pollutant (midpoint), and for freshwater and marine ecotoxicity in kg 1,4 DCB emitted to fresh- and seawater equivalent per kg of pollutant (midpoint). Human toxicity uses endpoint characterisation factors in order to better align with the valuation of human health used for social impacts. Human toxicity midpoint indicators (expressed in 1,4 DCB-eq) can be converted to DALY loss using the ReCiPe midpoint to endpoint conversion factors presented in Annex B. Toxicity midpoint characterisation factors are not included in Annex B: ReCiPe characterisation factors for modelling of air pollution, due to the extensive size of the ReCiPe dataset for this impact (1000+ pollutants).[15]

The footprint indicator of toxic emissions is calculated in the same way for air, soil and water pollution.

6.1.1. Pesticides

Use of pesticides (herbicides, fungicides, insecticides, rodenticides, etc) is the main source of toxic emissions in agriculture. In this method, it is modelled by looking at amounts of active ingredients which should be counted as emissions to agricultural soil. In ReCiPe, characterisation factors to estimate the impact of thousands of toxic chemicals used in agriculture are available. A correction for the amount of substance that does not reach the soil but remains on the crops can be applied if data is available.

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[15] ReCiPe 2016 midpoint characterisation factors for toxicity can be found on https://www.rivm.nl/en/life-cycle-assessment-lca/downloads.

In agriculture, other methods exist to assess the impact of pesticides, such as the *MilieuBelastingsPunten* in The Netherlands (Environmental Yardstick for Pesticides)[16] or the WHO Recommended Classification of Pesticides by Hazard (WHO, 2019b), and more. These are not based on LCA but highly relevant for the agri-food sector. If these methods are based on qualitative or semi-quantitative scales, they cannot be used to estimate impacts on people and the environment in a quantitative way, and therefore cannot be used for true pricing directly. These classifications of pesticides can however be useful to estimate the characterisation factors, if the active ingredients used in the value chain under study are not present in ReCiPe. In this case, characterisation factors could be estimated looking at those of pesticides with similar ranking of hazardousness (e.g., similar *MilieuBelastingsPunten*) that are present in ReCiPe.

6.2. Particulate matter (PM) formation

The ReCiPe lifecycle assessment methodology expresses particulate matter formation at the midpoint level in kg $PM_{2.5}$-eq using the PM formation potential (Huijbregts et al., 2017). This characterisation factor expresses the effects of a kilogram of specific pollutant to air in kg $PM_{2.5}$ equivalents.

6.3. Photochemical oxidant formation (POF)

The ReCiPe lifecycle assessment methodology expresses photochemical oxidant formation at the midpoint level in kg NO_x-eq using the human health and ecosystem damage ozone formation potentials (Huijbregts et al., 2017). These characterisation factors express the damage to human health and ecosystems of a kilogram of specific pollutant to air in kg NO_x equivalents.

6.4. Acidification

The ReCiPe lifecycle assessment methodology expresses acidification at the midpoint level in kg SO_2-eq using the terrestrial acidification potential (Huijbregts et al., 2017). This characterisation factor expresses the effect of a kilogram of NO_x, NH_3, and SO_2 emitted to air in kg SO_2 equivalents.

Regional accuracy of impact measurement

Annex H provides the method that accounts for the regional effects of particulate matter formation, photochemical oxidant formation and acidification (see Section 5). When data on pollutant level are available, it is recommended to follow that method rather than performing the characterization as specified in Sections 6.2, 6.3 and 6.4, respectively.

6.5. Ozone layer depleting emissions

Ozone layer depleting emissions are calculated by multiplying the amount of emissions in kg with the ozone depletion potential expressed in kg CFC11-eq/kg of pollutant, based on the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017). A complete list of the ozone depletion potential for different substances is provided in Annex B: ReCiPe characterisation factors for modelling of air pollution.

6.6. Nitrogen deposition

Nitrogen deposition, also known as terrestrial eutrophication, is linked to the emissions of NH_3 and NO_x and their deposition in nature areas. Emissions of these pollutants to the air can be derived by using

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[16] https://www.milieumeetlat.nl/ and https://www.pesticideyardstick.eu/

available models, such as the EMEP/EEA air pollutant emission inventory guidebook (EEA, 2019a) and the Hortifootprint Category Rules (Helmes et al., 2020).

6.7. Aquatic eutrophication

Aquatic eutrophication is mainly linked to the emissions of Nitrogen (N) and Phosphorus (P) to water bodies. It is expressed in two footprint indicators, namely freshwater eutrophication and marine eutrophication. Generally, Nitrogen (N) compounds are linked to marine eutrophication and Phosphorous (P) compounds to freshwater eutrophication because N is the limiting factor for growth of algae in the sea and P the limiting factor in freshwater. There can be local exceptions to this, even though this is the most common scope used for calculating eutrophication in LCA (Huijbregts et al., 2017).

The footprint indicators, both for freshwater and marine eutrophication, are calculated as the sum of direct emissions to water (emissions from point sources) and emissions from leaching/runoff of nutrients (diffuse emissions). Direct emissions are for example all discharges of pollutants and wastewater to water bodies. They are calculated by multiplying the amount of emissions of N and P compounds emitted to water by the N-eq and P-eq characterisation factors from the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017).

Emissions from leaching/runoff of nutrients are calculated by multiplying the leaching/runoff of N or P by the characterisation factors from the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017). These are primarily linked to all types of fertiliser application and typically have a big contribution to the water pollution impact in true price assessments[17]. It is possible to use other factors that are considered to be more representative of that region, to the extent that these are consistent with the methodology presented in this module, should such factors exist.

Leaching/runoff of nutrients to water bodies can be derived from LCA databases or modelled based on fertiliser application to farmland using existing methodologies. Note that leaching/runoff can vary greatly based on the methodology used. Special care should be taken to select the most appropriate method if an LCA database is not used. The Water Footprint Network grey water methodology (Liu et al., 2012) is a widely accepted methodology for estimating leaching/runoff to water from the application of fertiliser to soil.

- Additional explanation of the Water Footprint Network methodology and standard factors for calculating leaching/runoff for N and P are provided in Annex D: Leaching/runoff factors and characterisation factors for modelling of eutrophication.

6.8. Data requirements

The main datapoints needed for each process in the life cycle is either a list of pollutants emitted to air, soil and/or water in kg of pollutants, or a list of (midpoint) indicators corresponding to the indicators described above. A list of pollutants is equivalent to the Life Cycle Inventory (LCI) of an LCA.

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[17] To illustrate, fertiliser application containing N and P leads to leaching into water bodies and therefore contributes to eutrophication.

Regional accuracy of impact measurement

Annex H provides the method that accounts for the regional effects of particulate matter formation, photochemical oxidant formation and acidification (see Section 5). When data on pollutant level are available, it is recommended to follow that method.

If an LCA is not available many emissions of pollutants to air, soil and water at farm level can be estimated based on the use of agro-inputs on farm level. Below some examples are provided for illustration purposes:

- Fertiliser application rate in kg N and kg P can be used to calculate emissions to fresh-/marine water due to fertiliser application. The Water Footprint Network method presented in Section 6.7 and explained in Annex D: Leaching/runoff factors and characterisation factors for modelling of eutrophication, is a widely accepted source that could be used for this purpose, among other sources.
- Pesticide application, including the use of herbicides, insecticides, rodenticides and fungicides, can be converted to kg of active ingredients, for which a corresponding characterisation factor for toxic emissions to soil is available in the ReCiPe life cycle assessment methodology (Huijbregts et al., 2017).
- Electricity and fuel can use be converted to air pollution footprint indicators based on standard emissions factors from a widely accepted source.
- Data on the amounts of NH_3 and NO_x emitted to air can be derived by using available models, such as the EMEP/EEA air pollutant emission inventory guidebook (EEA, 2019a), the Hortifootprint Category Rules (Helmes et al., 2020) and the Methodology for estimating emissions from agriculture in the Netherlands, by Wageningen UR (Vonk et al., 2016).
- Waste generated in combination with factors representing emission per unit of waste managed.
- Data on the emissions to air caused during the manufacturing of agricultural inputs should also be collected.

7. Monetisation

7.1. Monetisation factors

The monetisation approach for the impacts of air, soil and water pollution is presented below. An overview of the global monetisation factors for all applicable indicators of air, soil and water pollution is presented in Table 1. All values are expressed at 2020 price level. Original values are inflated and converted, if needed, to euros to get the 2020 monetisation factors as presented in Table 1.

Table 1: Monetisation factors for air, soil and water pollution indicators and sub-indicators. Sources: (1) Biausque (2012); (2) Huijbregts et al. (2017); (3) de Groot et al. (2012); (4) OECD (n.d.a); (5) OECD (n.d.b); (6) Goedkoop et al. (2009); (7) de Bruyn et al. (2010); (8) Van den Born et al. (2020); (9) Prokofieva et al. (2011).

Indicator	Sub-indicator	Unit	Value - Global	Sources
Toxic emissions to air, soil and water	Human toxicity	EUR/DALY	103,048	(1)
	Terrestrial ecotoxicity	EUR/kg 1,4-DCB emitted to industrial soil eq	0.00025	(2) (3) (4)
	Freshwater ecotoxicity	EUR/kg 1,4-DCB emitted to freshwater eq	0.040	(2) (3) (5)
	Marine ecotoxicity	EUR/kg 1,4-DCB emitted to seawater eq	0.0018	(2) (3) (6)
Particulate matter (PM) formation		EUR/kg PM$_{2.5}$ eq	64.84	(1) (2)
Photochemical oxidant formation (POF)	Damage to ecosystems	EUR/kg NO$_x$-eq	2.85	(2) (3) (4)
	Damage to human health	EUR/kg NO$_x$-eq	0.09	(1) (2)
Acidification		EUR/kg SO$_2$-eq	4.68	(2) (3) (4)
Ozone layer depleting emissions		EUR/kg CFC11-eq	56.21	(1) (2) (7)
Nitrogen deposition	NH$_3$ from animal husbandry (in stables)	EUR/kg NH$_3$	12.7[18]	(8)
	NH$_3$ from use of manure	EUR/kg NH$_3$	8.1[14]	(8)
	NH$_3$ from other sources	EUR/kg NH$_3$	7.1[14]	(8)
	NO$_x$ from use of machines and vehicles	EUR/kg NO$_x$	1.2[14]	(8)
	NO$_x$ from other sources	EUR/kg NO$_x$	2.3[14]	(8)

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[18] For nitrogen deposition, the global value is an average of European values. For more information on the individual values for the different European countries included, see Annex F.2: Adjustment of nitrogen deposition monetisation factor for other European countries.

Freshwater eutrophication	EUR/kg P-eq to freshwater	203	(9)
Marine eutrophication	EUR/kg N-eq to marine water	14.07	(9)

Regional adjustment of monetisation factors

The monetisation factors provided in Table 1 are global averages and need adjustment to account for the region-specific effects.

Annex D provides the method to account for regional effects of eutrophication using region-specific characterisation factors in the impact quantification.

Annex F.2 provides the method to obtain monetisation factors for nitrogen deposition for European countries based on the PEF characterisation factors and data on the average accumulate exceedance per hectare.[19]

Annex H provides the method that accounts for the regional effects of particulate matter formation, photochemical oxidant formation and acidification (see Section 5). When data on pollutant level are available, it is recommended to follow that method.

7.1.1. Valuation of other ReCiPe midpoint indicators

The following global monetisation factors for midpoint indicators in ReCiPe 2016 can furthermore be derived with the method described in this chapter (Table 2). These factors are consistent with those presented in Table 1 above.

Table 2: Monetisation factors for ReCiPe 2016 midpoint indicators in 2020 prices.

Indicator	Unit	Value – Global
Human carcinogenic toxicity	EUR/kg 1,4 DCB	0.342
Human non-carcinogenic toxicity	EUR/kg 1,4 DCB	0.023
Ionising Radiation	EUR/kg Co-60 eq	8.76E-04

- See section 5.1 for more information on the correspondence with the ReCiPe method.

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[19] Characterisation factors of the Terrestrial Eutrophication method of the Product Environmental Footprint standard of the EU (PEF) and data on the average accumulate exceedance per hectare published by the European Environmental Agency are used for the adjustment.

7.2. Valuation approach

Different techniques are available to value environmental impacts. The monetisation factors are selected based on the **Valuation Framework for True Pricing Agri-Food Products** (Galgani et al., 2021b). They represent the cost to *remediate* negative impacts. Remediation cost consists of one or more types of costs, namely restoration, compensation, prevention, and retribution cost, selected according to a set of principles which consider the degree of reversibility, severity and illegality of an impact (Galgani et al. 2021b, Section 5). The following cost types apply to the environmental impacts discussed in this method:

- For **toxic emissions**, **particulate matter formation**, **photochemical oxidant formation, acidification** and **ozone layer depletion**, monetisation factors are based on damage cost (compensation cost), looking at human health damage, ecosystems damage, or both. For these impacts it is not possible to reverse the presence of pollutants in the environment once they are emitted, or the associated restoration cost is much higher than the damage cost. Damage to human health is valued using willingness to pay studies and ecosystems damage is valued looking at the value of ecosystems services lost.

- Section 7.3 describes the monetisation of human health and ecosystems.
- In Annex G: Supplementary information on monetisation of human health and ecosystem damage, a more detailed explanation of the monetisation approach is provided for these indicators, including clarification on how ReCiPe midpoint to endpoint conversion factors are used.

- For **eutrophication**, abatement cost is used (restoration cost). Restoration cost applies because the environmental damage caused is considered severe, as the Planetary Boundaries Framework the Nitrogen and Phosphorus flows to the biosphere and oceans are high risk boundaries (Stockholm Resilience Centre, n.d.)[20]. This applies to both **nitrogen deposition** and **aquatic eutrophication.** This is the same approach as used for valuation of Contribution to climate change (Galgani et al., 2021d).

- Section 7.4.1 and Annex F: Monetisation of nitrogen deposition, provide more information on the valuation of nitrogen deposition. Section 7.4.2 and Annex E: Monetisation of aquatic eutrophication, provide more information on the valuation of aquatic eutrophication.

Figure 3 below summarises the valuation approach used for each indicator.

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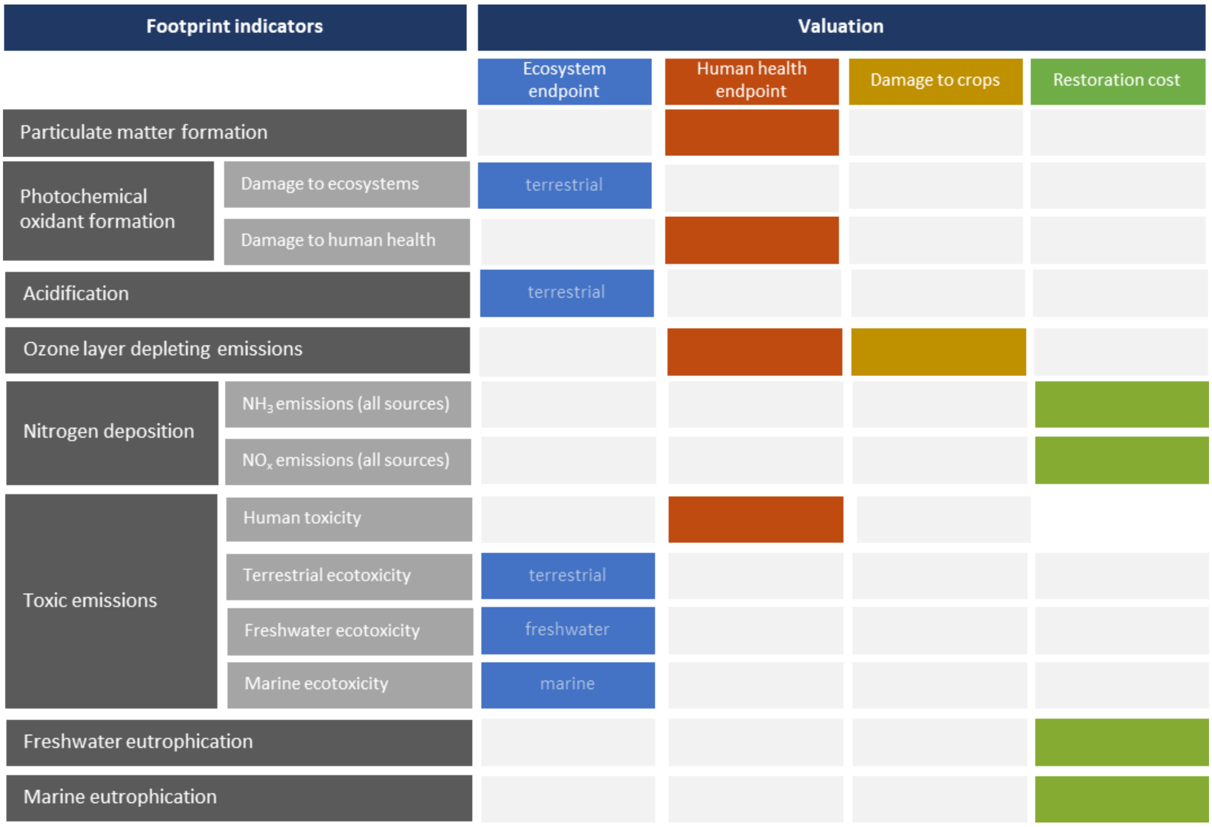
[20] The other high-risk boundary is climate change. Other planetary boundaries that relate to pollution and are not high-risk are Stratospheric ozone depletion, Chemical pollution and the release of novel entities and Atmospheric aerosol loading , which correspond here to ozone layer depletion, toxic emissions and PM formation and POF. See Stockholm Resilience Centre (n.d.) for more information.



Footprint indicators		Valuation			
		Ecosystem endpoint	Human health endpoint	Damage to crops	Restoration cost
Particulate matter formation			🟧		
Photochemical oxidant formation	Damage to ecosystems	terrestrial			
	Damage to human health		🟧		
Acidification		terrestrial			
Ozone layer depleting emissions			🟧	🟨	
Nitrogen deposition	NH_3 emissions (all sources)				🟩
	NO_x emissions (all sources)				🟩
Toxic emissions	Human toxicity		🟧		
	Terrestrial ecotoxicity	terrestrial			
	Freshwater ecotoxicity	freshwater			
	Marine ecotoxicity	marine			
Freshwater eutrophication					🟩
Marine eutrophication					🟩

Figure 3: Valuation approach used for each indicator.

7.3. Endpoint valuation: human health and ecosystem damage

For toxic emissions, particulate matter formation, photochemical oxidant formation, acidification and ozone layer depletion, the monetisation factors are based on compensation cost. These costs are estimated using endpoint valuation: the valuation of human health damage and ecosystem damage. This approach uses ReCiPe 2016 midpoint to endpoint conversion factors (Huijbregts et al., 2017) for each indicator, together with standard damage cost factors for human health and ecosystems.

7.3.1. Human health damage valuation

In the true price method, the endpoint of **human health** is used explicitly for the valuation of human toxicity and implicitly for three other indicators of air pollution: ozone layer depletion, particulate matter formation and photochemical oxidant formation: damage to human health, based on valuation of a DALY (Disability Adjusted Life Year). In addition, the value of human health is used in the monetisation of several social impacts, which will be covered in separate modules. The DALY is a standard unit for measuring health effects (WHO, 2019a). The monetary value of a DALY is the main element of human health valuation in this method.

There is no scientific consensus as of what monetary value of 1 DALY to use in the valuation of human health, let alone for the specific case of assessment of externalities of products. The European Commission suggests using a range of EUR 50,000 to 100,000 for a VOLY (Value of a Life Year) when valuing the damage to human health due to pollution (EC, 2009a; EC, 2009b). CE Delft (de Bruyn et al., 2018a) originally values DALY using a central value of EUR 70,000 for a VOLY.[21] CE Delft uses as a point of departure the value of a

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[21] It is assumed that 1 DALY equals 1 VOLY.

VOLY given in the NEEDS project for the EU-15, which is EUR 48,000 in 2015 prices. Based on values reported in other studies, they define the lower value of a VOLY at EUR 50,000 and its upper value around EUR 110,000 and assume a central value of EUR 70,000.

No regional correction for income levels is applied, and this value is used both in the NL (de Bruyn et al., 2018a) and EU (de Bruyn et al., 2018b) versions of their Environmental Prices Handbook. However, for human toxicity, CE Delft (de Bruyn et al., 2018a) uses a different VOLY/DALY value of EUR 55,000, taken from their previous Handbook Shadow Prices (de Bruyn et al., 2010). CE Delft notes that for heavy metals there is a big difference between the upper and lower value, which is also due to scientific uncertainty about the dispersion of toxic pollutants in the food chain and the impact on human health.

The monetary value of a DALY based on a meta-analysis of 92 willingness-to-pay studies carried out by the OECD in 2012 is selected here. They published average values for the Value of Statistical Life (VSL). The average VSL for health is 2,574,140 US$ (Biausque, 2012, Table 1, p.12 2005 price level). An average valuation of one Year of Life Lost (YLL, assumed to be valued the same as a DALY) of 86,750 US$ can be derived by dividing this VSL by the average life expectancy of the respective respondents of the studies included in the meta-analysis (equal to 29.67 years, determined as the difference between the average life expectancy and the average age of respondents of each study[22]). This is equivalent to EUR 103,048 (2020 price level)[23].

The DALY value derived from OECD (Biausque, 2012) is similar to the upper bound of the range provided by CE Delft (de Bruyn et al., 2018a) and EC (2009a; 2009b) for the value of a VOLY. However, we consider it preferable for the valuation of human health compared to the central value used by CE Delft (de Bruyn et al., 2018a), since it is based on a meta-analysis of values from different countries carried out by an international institution and correcting for differences in price levels.[24] Therefore, for the purpose of true pricing a DALY value of EUR 103,048 at 2020 price level is proposed. The value is not adjusted for countries with different income and living costs and can be used globally. More information on this can be found in Annex G: Supplementary information on monetisation of human health and ecosystem damage.

7.3.2. Ecosystem damage valuation (biodiversity)

In the true price method, the endpoint of **ecosystems damage** is used for the valuation of acidification, photochemical oxidant formation: damage to ecosystems, terrestrial, marine and freshwater ecotoxicity.[25] Damage to ecosystems in this module is valued in terms of impacts on **biodiversity**.[26] Impacts on biodiversity of each indicator are measured in PDF.m^2.yr (PDF = Potentially Disappeared Fraction of species) and modelled using ReCiPe mid-to-endpoint factors (Huijbregts et al., 2017).

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[22] The dataset with average age of respondents in each study is available here https://www.oecd.org/env/tools-evaluation/env-value-statistical-life.htm

[23] This is based on the original value of US$$_{2005}$ of 86,744, which is equal to EUR$_{2016}$ 98,347 based on an inflation rate of 1.255 for the US and an exchange rate to euro of 0.9034 (World Bank data). The accumulated inflation to 2020 (1.0479) gives the final value of EUR 103,048.

[24] This study is also mentioned as a notable source on the valuation of human health impacts in the CE Delft publication (de Bruyn et al., 2018a), which highlights that the French government has used the same OECD study to derive the recommended value of EUR 115,000 for a VOLY in cost-benefit analyses.

[25] Ozone layer depleting emissions also includes damage to ecosystems, though the approach for its valuation differs from the one described in this section. For more information on this see section **Error! Reference source not found.** and Annex G: Supplementary information on monetisation of human health and ecosystem damage

[26] For more information on the relationship between ecosystems, ecosystem services and biodiversity consult the impact-specific module **Land use, Land use change, Biodiversity and Ecosystems Services** (Galgani et al. 2021c).

There is no scientific consensus as of what value to use in valuation of biodiversity loss. A variety of values for PDF valuation is available in the literature, all with their own assumptions and valuation approaches. Ott et al. developed an assessment approach based on the restoration cost method for the NEEDS project (Ott et al., 2006). This approach uses the inverse of the relative species' abundance, called the **Potentially Disappeared Fraction** (PDF).[27] For an increase of species the PDF value decreases, and vice versa. NEEDS assigns different PDFs to different land use types. The restoration cost method evaluates the cost for restoring different starting biotopes into different target biotopes (in EUR/m^2), measured with PDF-changes by habitat restoration, and discounted to obtain **annual** values (Ott et al., 2006). The project comes to EU25 values that range between 0.03 and 0.40 EUR/ PDF.m^2.yr for various starting and target biotopes (Ott et al., 2006, as quoted by Kuik et al. 2007 p. 11, 2004 price level).

Another report that assesses and values biodiversity, based on a meta-analysis of 160 economic studies related to land use and biodiversity loss, is the CASES project (Kuik et al., 2007). Kuik et al. developed a willingness to pay function, an alternative to the restoration cost approach developed by Ott et al., to estimate for changes in biodiversity for different European countries. Land use changes are described in terms of Ecosystems Damage Potential (EDP) to account for impacts on biodiversity. The authors state that EDP and PDF are considered equal. The standardised monetary value of Euros per EDP.ha.yr is used for the meta-analysis, while the average EU value estimated from the report's dataset is 4,706 EUR/ EDP.ha.yr and the median is 604 EUR/EDP.ha.yr (Kuik et al., 2007, p.18, 2004 price level). These values are equal to 0.47 EUR/ PDF.m^2.yr and 0.06 EUR/PDF.m^2.yr.

The CE Delft handbooks of environmental prices make use of Ott et al. (2006) and Kuik et al. (2007) to provide a range of biodiversity loss valuation factors. Low, central and upper values are available for Dutch-specific and EU28 impacts on biodiversity. However, due to the high range in these sources and different methodological assumptions the resulting values have a large variation between the EU and Dutch handbook. The central value for the Netherlands is equal to 0.48 EUR/ PDF.m^2.yr (de Bruyn et al., 2018a, p.71, 2004 price level), based on the average value of Ott et al. (2006), while the EU one is equal to 0.06 EUR/ PDF.m^2.yr (de Bruyn et al., 2018b, p. 73, 2004 price level), based on the median value of Kuik et al. (2007). Dutch values from Kuik et al. (2007) are adjusted for population density and average size of nature areas in the Netherlands in the Dutch version of the report.

Ultimately valuation of biodiversity using PDF is uncertain and many approaches are available, but each has its own limitations and no standardised method exists. For this reason, a biodiversity valuation approach has been developed which is consistent with the one used to value biodiversity loss due to land use (Galgani et al., 2021c). In that method MSA is being used as a biodiversity indicator, which is a more sensitive indicator as PDF, but being both indicators of biodiversity loss compared with a native state they are considered similar.

The valuation of ecosystem damage in this module is based on the annual value of ecosystem services (ESS) of one hectare of nature, based on the median annual value per hectare of ecosystem services of six terrestrial biomes.[28] These values are based on a published meta-analysis of the TEEB database (de Groot

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[27] '*PDF is an indicator of ecosystem damage that expresses the risk of species extinction as a result of emissions, land-use changes and other deleterious factors. The current assemblage of plant and animal species under a certain land-use regime (Si) is compared with a reference regime (Sref) to give the relative species richness, the inverse of which is PDF: PDF = 1-Si/Sref*' (de Bruyn et al., 2018a). ReCiPe provides species density factors to convert their endpoint ecosystem damage values in species.yr to PDF.m^2.yr (Huijbregts et al. 2017).

[28] Biomes included are tropical forest, other forest, woodland/shrubland, grassland/savannah, inland wetland and coastal wetland.

et al., 2012). In the **Land use, Land use change, Biodiversity and Ecosystems Services** (Galgani et al., 2021c) module, these values in EUR/ha.yr are used to monetise land occupation (which is biodiversity-adjusted and measured in MSA.ha.yr) and represent the opportunity cost of using the land and displacing ecosystems. MSA stands for Mean Species Abundance, a comparable metric of biodiversity to PDF, and PDF.m^2 is a comparable unit to MSA.ha (as also noted in PBAF, 2020, p. 20). The values of ecosystem services of all terrestrial biomes from the TEEB database (de Groot et al., 2012) can therefore be used to calculate a global monetary value for loss of biodiversity measured in PDF.m^2.yr. This is based on the above-mentioned median ESS values per hectare by biome and average land cover of those six biomes in the world from OECDstat (OECD, n.d.a).

With this approach an average global value of biodiversity loss in terrestrial ecosystems is derived, which for 2020 is equal to 0.33 EUR/PDF.m^2.yr. The steps to derive these values are illustrated in Annex G.

Marine and freshwater ecotoxicity are indicators related to biodiversity loss in aquatic ecosystems and require an adjusted approach. The median monetary value of ecosystem services of open oceans is utilised to derive a PDF value for marine ecotoxicity, while the value of rivers and lakes is utilised for freshwater ecotoxicity. These values are equal to 0.012 EUR/PDF.m^2.yr and 0.35 EUR/PDF.m^2.yr respectively for 2020.

It should be noted that certain assumptions have been made in order to derive the above monetary values for ecosystems damage.

- Firstly, ESS and biodiversity are assumed to scale linearly. This allows for the valuation of ESS, expressed in ha.yr, to be utilised for the valuation of biodiversity, expressed in PDF.m^2.yr. This might be viewed as an oversimplification, but it is intrinsic to the use of PDF, a relative biodiversity indicator, as a measure of ecosystem damage. Since PDF is regarded as one of the most suitable biodiversity indicators from various sources (PBAF, 2020; Ott et al., 2006; Kuik et al., 2007; de Bruyn et al., 2018a; Huijbregts et al., 2017), this assumption is accepted for the purposes of this methodology and the same assumption is applied for the use of the MSA indicator in the land occupation method.
- Additionally, for terrestrial ecosystems a global value is preferred rather than location specific values, due to the high uncertainty and the fact that the quantification of ecosystems damage from ReCiPe is not location specific (e.g., it is not specified where the damage occurs, only the size of the damage).
- Finally, desert biomes are excluded from the calculation of a global value of ESS per hectare of nature. This is based on the fact that this specific land type is rarely used by humans in order to conduct activities that can potentially lead to external costs. This choice might lead to a possible overestimation of the values.

- For more explanation on how ReCiPe midpoint to endpoint conversion factors for ecosystems damage are utilised for the monetisation of the different indicators see Annex G.
- For full background on land use, biodiversity and ecosystem services in the true price method, consult the impact-specific module **Land use, Land use change, Biodiversity and Ecosystems Services** (Galgani et al., 2021c).

7.3.3. Additional damage costs for ozone layer depleting emissions

The monetisation factor for **ozone layer depleting emissions** consists of two types of costs. Besides the endpoint valuation of damage to human health (as explained in Section 7.3.1), also the cost of damage to agricultural crops is included. The cost of damage to agricultural crops represents average damage costs for ozone depletion for an average emission source in the Netherlands taken from CE Delft (de Bruyn et al., 2018a). Although the damage could be different in different geographies, for example because of different thickness of the ozone layer, at the moment the value is used without adjustments for all countries due to the lack of an appropriate coefficient for regional adjustments.

7.4. Midpoint valuation

7.4.1. Nitrogen deposition

In calculating the contribution to the true price of **nitrogen deposition**, the marginal cost of the abatement measures needed to reach the regulatory target of nitrogen deposition in nature areas is considered. A cost of 3.40 EUR_{2020}/µmol N/ha/yr derived for The Netherlands by Van der Born et al. (2020) is the starting point. Table 3 shows how different types of emissions contribute to nitrogen deposition (based on Van der Maas, 2020) and how this leads to different monetisation factors.

- The methodology for deriving these factors is presented in Annex F.1: Derivation of monetisation factor.
- Factors for other European countries are provided in Annex F.2: Adjustment of nitrogen deposition monetisation factor for other European countries, which also includes a map of eutrophication risk in Europe.

Table 3: Monetisation factors for nitrogen deposition in the Netherlands, for all processes that lead to gas emissions with different Nitrogen deposition effects in soil, price level 2020. Source for column (a) is Van der Maas (2020); column (b) is derived from Van der Born et al. (2020)

Gas	Application	(a) Assumed additional deposition from additional emission (µmol N/ha/yr) / kg in the Netherlands	(b) Costs (EUR) to prevent the deposition of 1 µmol N/ha/yr in the Netherlands	(a*b) Contribution to the true price gap per kg gas emission (EUR/kg emitted)
NH_3	Animal husbandry (in stables)	7.30	3.40	24.8
NH_3	Use of manure	4.60	3.40	15.6
NH_3	Other	4.00	3.40	13.6
NO_x	Use of agricultural machines and vehicles	0.79	3.40	2.69
NO_x	Other	1.50	3.40	5.10

The compensation costs (as described in 7.3) do not account for the additional effects from deposition of nitrogen. However, the current module only provides a method to include abatement costs for nitrogen deposition for European countries (see Annex F.2) due to a lack of country-specific data on eutrophication risks. Therefore, this impact can currently not be accounted for outside of European countries.

7.4.2. Freshwater and marine eutrophication

The monetisation factors for **freshwater** and **marine eutrophication** represent an abatement cost, based on a meta-analysis by Prokofieva et al. (2011). Abatement cost expresses the cost for restoring nutrient levels down to a regulatory target and are used for the impacts that are reversible.

- A discussion of these factors is provided in Annex E: Monetisation of aquatic eutrophication.

8. Uncertainty, limitations and items for further research

8.1. Uncertainty

Modelling of pollution impacts and their external costs comes with uncertainty, as for all impacts in true pricing. Different layers of uncertainty in a true pricing model exist, affecting different aspects of the current study:

- **Uncertainty of scope:** different methodological choices in the scoping phase, such as the system boundaries, the impacts to include, and assumptions related to time, technological, geography, etc., can introduce uncertainty.
- **Uncertainty of process data:** uncertainty that arises when data of lower quality (old data or background data for a market average, for a similar product or for another country) are used to estimate pollution of a specific value chain's product. This is relevant, among others, for the data that describes the agricultural processes.
- **Uncertainty of modelling parameters:** uncertainty that arises from choices and assumptions made to obtain modelling parameters. In this method, this uncertainty comes with the monetisation factors models and the use of models developed elsewhere, such as the ReCiPe conversion factors and other parameters used for quantifying the footprint indicators, or for the endpoint valuation approach (DALY and PDF.m^2.yr estimation). ReCiPe does not provide uncertainty ranges, while the sources used for DALY and PDF.m^2.yr valuation do provide some uncertainty parameters (Biausque, 2012; De Groot et al., 2012).

Recommendations and requirements for dealing with uncertainty in data collection and in testing of the results are given separately in the **True Pricing Assessment Method for Agri-food Products** (Galgani et al., 2021a). The general principles are the following:

- The approach for dealing with uncertainty depends on the desired use of the results, where the more a study is aimed at public comparisons between products, the more accuracy, quantitative insight into and disclosure of uncertainty is required.
- Lack of data is not a reason to leave an impact out of scope. It is preferable to include an uncertain value based on the best possible estimate than not including the indicator at all, as that would give the impression that the cost is not present.
- The best available estimate and data ought to be used.
- Uncertainty can be assessed by comparing different sources in a literature review, a review by experts or by estimating uncertainty ranges with statistical techniques such as Monte Carlo Analysis.
- Resources invested in data collection to reduce or quantify uncertainty should focus on the most material impacts for the specific product under study.
- Uncertainty and its implications should be disclosed in reporting.

8.2. Limitations

- A restoration cost could be appropriate for the valuation of ecosystem damage and human health, following the Valuation Framework, since this damage is severe and reversible. However, since air pollution has effects that are diffused, these damages are not localised to specific locations or groups of people, and therefore restoration is not always an option. Additionally, for ecosystems a well-documented, peer reviewed applicable source regarding restoration cost, is not yet available.

- The utilisation of PDF to value biodiversity and ecosystems damage in this module comes with high uncertainty, yet it is common practice for ecosystems valuation. It is preferable to include such an approach in order to monetise the different pollution indicators, rather than excluding damage to ecosystems in the monetisation approach completely. Additionally, it is preferable to keep an approach to value biodiversity loss which is consistent with other impact modules of the true price assessment (namely with the impact-specific module **Land use, Land use change, Biodiversity and Ecosystems Services** (Galgani et al., 2021c)).
- Conversion of ecosystem damage from species.yr to PDF.m^2.yr involves uncertainty, both in the way it is applied in ReCiPe as well as the adaptations done in this method. Regarding the latter, in particular converting average species density in aquatic environments, from species/m^3 to species/m^2, with average depth in which species can be found, causes uncertainty on the final monetisation factors of freshwater and marine ecotoxicity.
- For nitrogen deposition, the proximity of the source of emission to nature-prone areas is an important aspect, so the use of country average values for monetisation is an important limitation. The density of nature areas differs in different regions and not all areas are prone to terrestrial eutrophication. So, dairy situated in one region would have a different impact than in other regions.
- The effects of ozone depletion to human health come with some uncertainty. According to CE Delft (de Bruyn et al., 2018a; de Bruyn et al., 2018b) some effects can happen in the long term, resulting in a substantial difference between the individualist perspective and the hierarchist perspective valuation, which refers to the time horizon in which damage is modelled.
- No country-specific/regional monetisation factors for PM, POF and acidification indicators are provided. An alternative approach based on monetisation factors of the pollutants contributing to the regional effects is provided (see Annex H). However, this approach requires data of the emitted amounts of specific pollutants.

8.3. Items for further development

- Develop datasets to aid quantification, such as standard factors to streamline the quantification of air, soil and water pollution in agri-food products and chains. Standard factors to estimate pollution indicators starting from using of agricultural inputs in different circumstances could be derived. This would allow a rapid assessment of pollution based on data that is already available to businesses in the sector.
- Expand the forms of pollution considered to include, for example, pharmaceutical emissions from livestock, plastic pollution, or ionizing radiation.
- Develop a more sophisticated approach to value ecosystem damage (biodiversity loss) in different geographical contexts.
- Develop materiality tools to help determine quickly for which part of the chain which indicators should be quantified when there is no LCA available.
- Regarding nitrogen deposition, analyse in more detail the effects of proximity to Nitrogen-sensitive areas. The currently proposed model does not correct for proximity to Nitrogen-sensitive areas, while this is in fact a very important factor.
- Develop weighted-average midpoint to endpoint conversion factors for particulate matter formation, photochemical oxidant formation and acidification emissions for individual countries, based on the ReCiPe method. Subsequently, develop country-specific monetisation factors for the relevant indicators.

- The regional specificity of the current method is limited to the country-level. However, the effects of pollution depend on region-specific circumstances. For example, the impact on human health following PM intake depends, amongst others, on the population density around the emission source and the height of the emissions (Humbert et al., 2011). The country-specific monetisation factors in the current module allow for valuation of the effects of pollution on a country-average level. Further regionalisation of the factors would allow for quantification and valuation at, for example, urban, rural or remote areas. A similar approach as taken by CE Delft, following findings from Humbert et al. (2011) could be followed (CE Delft, 2023).

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Annex A: Link with internationally accepted agreements on the rights of current and future generations

The *right to a safe, clean, healthy and sustainable environment* is recognised in regional UN agreements and most national constitutions and is reflected in the following international agreements:

- The Framework Principles on Human Rights and the Environment, which state that '*States should ensure a safe, clean, healthy and sustainable environment in order to respect, protect and fulfil human rights.*' (UN Human Rights Special Procedures, 2018)
- The Resolution adopted by the Human Rights Council on 22 March 2018, 37/8 recognises that
  - '*The impact of climate change, the unsustainable management and use of natural resources, the unsound management of chemicals and waste, the resulting loss of biodiversity and the decline in services provided by ecosystems may interfere with the enjoyment of a safe, clean, healthy and sustainable environment, and that environmental damage can have negative implications, both direct and indirect, for the effective enjoyment of all human rights*.' (UN General Assembly, 2018)
  - '*More than 100 States have recognized some form of a right to a healthy environment in, inter alia, international agreements, their constitutions, legislation or policies*.' (UN General Assembly, 2018)
- The Declaration of the United Nations Conference on the Human Environment establishes the following (UN, 1972):
  - '*The principle to not discharge of toxic substances in such quantities or concentrations as to exceed the capacity of the environment to render them harmless*.'
  - '*All possible steps should be taken to prevent pollution of the seas.*'
- The so-called Brundtland Report 'Our Common Future' states that (Brundtland, 1987):
  - '*Clean air and water, and the protection of natural beauty should be incorporated in the view of human needs and well-being*.'
  - '*Adverse impacts on the quality of air, water, and other natural elements should be minimized*.'
- The UN Sustainable Development Goals (SDGs) also talk specifically about water and air pollution:
  - '*Ensure availability and sustainable management of water and sanitation for all*.' (SDG 6, UN General Assembly, 2015)
  - '*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*.' (SDG 6, SDG 14, UN General Assembly, 2015)
  - '*Make cities and human settlements inclusive, safe, resilient and sustainable*.' (SDG 11, UN General Assembly, 2015). This SDG is linked to air quality and pollution, as shown by the progress report of 2019, which mentioned that '*Urgent action is needed to reverse the current situation, which sees the vast majority of urban residents breathing poor-quality air* […].' (UN Economic and Social Council - ECOSOC, 2019).
  - '*Ensure healthy lives and promote well-being for all at all ages*.' (SDG 3, UN General Assembly, 2015). This SDG is linked to air quality and pollution, as shown by the progress report of 2019, where it's mentioned that '*Concerted efforts are required* […] *to tackle antimicrobial resistance and determinants of health such as air pollution* […].' (UN Economic and Social Council - ECOSOC, 2019).

The right to a safe and clean drinking water is recognised by the resolution adopted by the UN General Assembly on 28 July 2010 64/292, *The human right to water and sanitation*, which recognises '*The right to safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of life and all human rights*'.

The right of everyone to the enjoyment of the highest attainable standard of physical health is reflected in several international agreements:

- The International Covenant on Economic and Social Council establish '*The right of everyone to the enjoyment of the highest attainable standard of physical and mental health*.' (UN Human Rights Office of the High Commissioner, 1976)
- The UN Sustainable Development Goals (SDGs) sets the goal to '*Ensure healthy lives and promote well-being for all at all ages*' (SDG 3, UN General Assembly, 2015)

Annex B: ReCiPe characterisation factors for modelling of air pollution

Quantifying midpoint footprint indicators for air pollution requires so called midpoint characterisation factors. An overview of standard characterisation factors from ReCiPe (Huijbregts et al., 2017) for the footprint sub-indicators of particulate matter formation, acidification and ozone layer depleting emissions are provided in the tables below for convenience (the tables are taken directly from Huijbregts et al., 2017). ReCiPe offers factors for three perspectives (individualist, hierarchist and egalitarian) depending on the value choices done in modelling[30]. It is recommended to use the Hierarchist perspective, which is based on scientific consensus. For photochemical oxidant formation a complete list of the human health and ecosystem potentials of individual NMVOC substances, in NO_x-eq/kg of substance, can be found in the ReCiPe documentation (Huijbregts et al., 2017, p. 135-138, 141-145).

Table 4: World average midpointcharacterisation factors for different substances contributing to particulate matter formation. Reprinted from Huijbregts et al., 2017, p. 53.

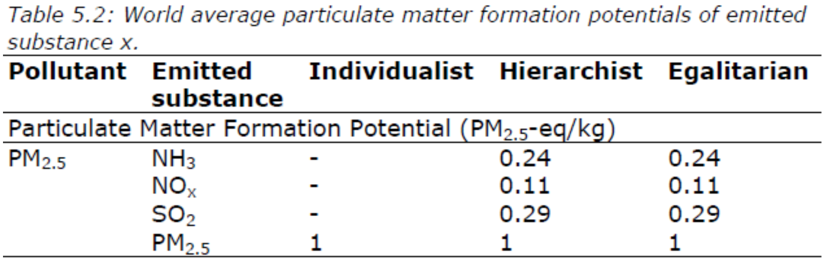

Table 5.2: World average particulate matter formation potentials of emitted substance x.

Pollutant	Emitted substance	Individualist	Hierarchist	Egalitarian
Particulate Matter Formation Potential ($PM_{2.5}$-eq/kg)				
$PM_{2.5}$	NH_3	-	0.24	0.24
	NO_x	-	0.11	0.11
	SO_2	-	0.29	0.29
	$PM_{2.5}$	1	1	1

Table 5: World average midpoint characterisation factors for different substances contributing to acidification. Reprinted from Huijbregts et al., 2017, p. 63.

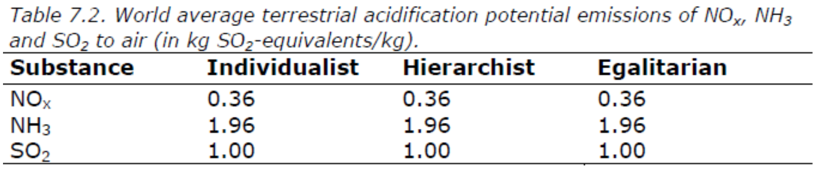

Table 7.2. World average terrestrial acidification potential emissions of NO_x, NH_3 and SO_2 to air (in kg SO_2-equivalents/kg).

Substance	Individualist	Hierarchist	Egalitarian
NO_x	0.36	0.36	0.36
NH_3	1.96	1.96	1.96
SO_2	1.00	1.00	1.00

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[30] *"The individualistic perspective is based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation. The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms. The egalitarian perspective is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available"* (Huijbregts et al. 2017)

Table 6: World average midpoint characterisation factors for different substances contributing to ozone layer depletion. Reprinted from Huijbregts et al., 2017, p. 41.

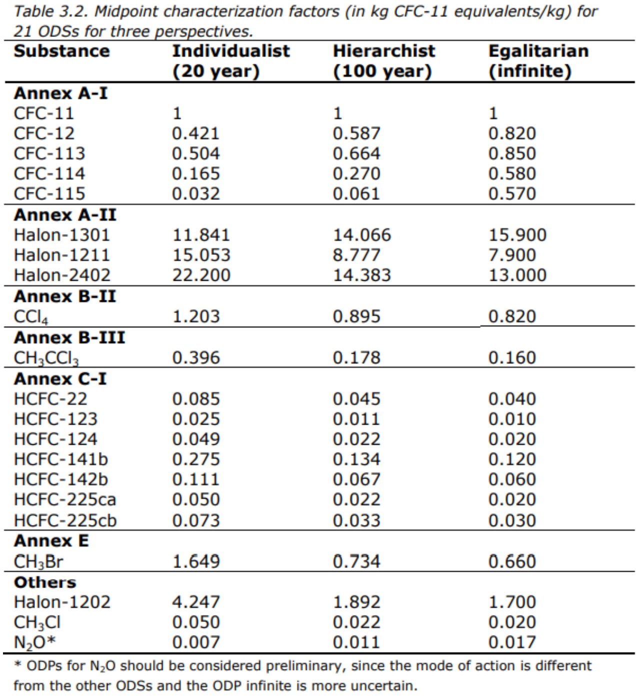

Table 3.2. Midpoint characterization factors (in kg CFC-11 equivalents/kg) for 21 ODSs for three perspectives.

Substance	Individualist (20 year)	Hierarchist (100 year)	Egalitarian (infinite)
Annex A-I			
CFC-11	1	1	1
CFC-12	0.421	0.587	0.820
CFC-113	0.504	0.664	0.850
CFC-114	0.165	0.270	0.580
CFC-115	0.032	0.061	0.570
Annex A-II			
Halon-1301	11.841	14.066	15.900
Halon-1211	15.053	8.777	7.900
Halon-2402	22.200	14.383	13.000
Annex B-II			
CCl_4	1.203	0.895	0.820
Annex B-III			
CH_3CCl_3	0.396	0.178	0.160
Annex C-I			
HCFC-22	0.085	0.045	0.040
HCFC-123	0.025	0.011	0.010
HCFC-124	0.049	0.022	0.020
HCFC-141b	0.275	0.134	0.120
HCFC-142b	0.111	0.067	0.060
HCFC-225ca	0.050	0.022	0.020
HCFC-225cb	0.073	0.033	0.030
Annex E			
CH_3Br	1.649	0.734	0.660
Others			
Halon-1202	4.247	1.892	1.700
CH_3Cl	0.050	0.022	0.020
N_2O*	0.007	0.011	0.017

* ODPs for N_2O should be considered preliminary, since the mode of action is different from the other ODSs and the ODP infinite is more uncertain.

Table 7: Midpoint to endpoint conversion factors for Human Toxicity. Reprinted from Huijbregts et al., 2017, p. 80.

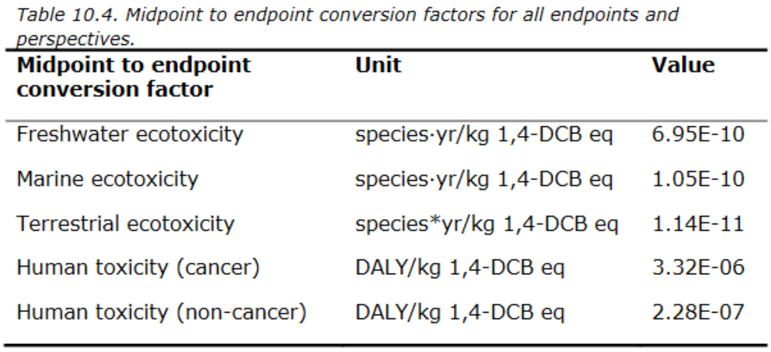

Table 10.4. Midpoint to endpoint conversion factors for all endpoints and perspectives.

Midpoint to endpoint conversion factor	Unit	Value
Freshwater ecotoxicity	species·yr/kg 1,4-DCB eq	6.95E-10
Marine ecotoxicity	species·yr/kg 1,4-DCB eq	1.05E-10
Terrestrial ecotoxicity	species*yr/kg 1,4-DCB eq	1.14E-11
Human toxicity (cancer)	DALY/kg 1,4-DCB eq	3.32E-06
Human toxicity (non-cancer)	DALY/kg 1,4-DCB eq	2.28E-07

Annex C: Comparison between ReCiPe and USEtox methods for quantifying toxicity

The true price assessment method presented in this module quantifies toxicity using the ReCiPe methodology. It contains a database with characterisation factors that estimate how much human or eco-toxicity is created by emission of 1 kg of >3000 pollutant to air, soil or water, with factors based on how stable a pollutant is in the environment, where it is likely to be transported, and how dangerous it is for life (fate, exposure and effect). Table 8 lists the toxicity indicators from the ReCiPe methodology that are included in this module.

Table 8: Toxicity indicators in this module from ReCiPe (Huijbregts et al., 2017).

Indicator	Unit
Human toxicity[31]	DALY
Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq
Freshwater ecotoxicity	kg 1,4-DB emitted to freshwater eq
Marine ecotoxicity	kg 1,4-DB emitted to seawater eq

USEtox was developed as a “scientific consensus” model endorsed by the UNEP/SETAC Life Cycle Initiative for characterising human and ecotoxicological impacts of chemicals (Fantke et al., 2017). It is a widely used method for quantifying impacts of toxic pollutants and it also provides factor for >3000 pollutants. It is also adopted by PEF, in a version that has been adapted using physicochemical and toxicity data available in the REACH-IUCLID database from the European Chemical Agency (ECHA), the OpenFoodTox database from the European Food Safety Authority (EFSA) and from the Pesticide Properties Database (PPDB) from the University of Hertfordshire.

USEtox has factors for human and freshwater ecotoxicity.

Table 9: Toxicity indicators from USEtox (Fantke et al., 2017).

Indicator	Unit
Human toxicity – carcinogenic	CTUh (midpoint) or DALY (endpoint)
Human toxicity – non-carcinogenic	CTUh (midpoint) or DALY (endpoint)
Freshwater ecotoxicity	CTUe (midpoint) or PAF (endpoint)

Since USEtox is a method with scientific consensus, it should be the preferred method. In the long term, the true price assessment method should move towards using USEtox, but for now ReCiPe has been used as a reference. The main reasons to choose ReCiPe over USEtox are:

- ReCiPe has a broader coverage of indicators (including marine and terrestrial ecotoxicity). USEtox only includes human toxicity and freshwater ecotoxicity. Terrestrial ecotoxicity is particularly important for agriculture due to the use of pesticides and their influence on insects.

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[31] Sum of carcinogenic and non-carcinogenic toxicity

- Even though USEtox is called a “consensus model” for toxicity, two different versions exist (main one by UNEP, adapted version by PEF). It is not clear which one is preferable and what are the differences in practice.
- ReCiPe 2016 is the base method used to quantify most of the air, soil and water pollution impacts besides toxicity in true price assessment method. It is a well-accepted method and builds on the USEtox model.

It is recommended to review this choice in the coming years.

Annex D: Leaching/runoff factors and characterisation factors for modelling of eutrophication

Modelling leaching/runoff of N and P

Calculating emissions from fertiliser application requires modelling the amount of N and P leached. The Water Footprint Network grey water footprint accounting methodology (Franke et al., 2013) provides a formula and standard coefficients for that purpose:

$$L = \alpha \; x \; Appl \; (mass/time) \tag{2}$$

Where the dimensionless factor alpha (α) stands for the leaching-runoff fraction, defined as the fraction of applied chemical substances reaching freshwater bodies. The variable $Appl$ represents the application of chemical substances on or into the soil (in mass/time), i.e., artificial fertilisers, manure or pesticides put on croplands, urine deposits on pastures by grazing animals, solid waste or sludge put in landfills, etc. (Franke et al., 2013).

The method provides three standard α coefficients: a minimum, an average and a maximum one, as shown in Table 10. We recommend using the average values unless specific reasons are present to differ. If this is suspected, for example due to high efficiency of nutrient use, specific soil or climate characteristics, consult the grey water footprint accounting methodology (Franke et al., 2013) to derive more appropriate factors.

The method assumes that a fraction of the applied chemical substances finally reaches the ground or surface water. Whether the nutrients end up in sea/freshwater is not a point of consideration.

Table 10: Overview of leaching/runoff coefficient (α) for Nitrogen and Phosphorus. Adapted from Franke et al., 2013.

α-coefficient	**N**	**P**
Minimum leaching/runoff coefficient (α_{min})	0.01	0.0001
Average leaching/runoff coefficient (α_{avg})	0.1	0.03
Maximum leaching/runoff coefficient (α_{max})	0.25	0.05

Suggested characterisation factors for modelling aquatic eutrophication

Aquatic eutrophication is modelled based on LCA and it is suggested to use for that purpose the characterisation factors from ReCiPe methodology (Huijbregts et al., 2017).

These are the midpoint factors for eutrophication and represent ecosystem damage potential (residence time) compared to global average for a direct emission to fresh-/marine water. The factors are expressed in kg P to freshwater-eq/kg P to freshwater or kg N to marine water-eq/kg N to rivers.

For Nitrogen, which contributes to marine eutrophication, emission can occur both in freshwater and seawater. For emissions to freshwater, transport all the way to seawater is modelled, including removal at watershed and river level. A characterisation factor with continent-specific values is given by ReCiPe, as shown in Table 11.

The characterisation factor is 1 for direct emissions to seawater. A higher factor means that Nitrogen emitted to freshwater has a higher chance to end up contributing to seawater eutrophication.

Table 11: Continent-specific midpoint characterisation factors for marine ecosystem damage (kg N-eq/kg). Adapted from Huijbregts et al., 2017, p. 167-168.

Region	Midpoint characterisation factor (N)
Africa	0.12
Europe	0.84
North America	0.13
South America	0.10
North Asia	0.48
South Asia	0.33
Oceania	0.21
Australia	0.07

For Phosphorus, which contributes to freshwater eutrophication, a country-specific factor is used that expresses average permanence in freshwater relative to global average (85 days). This factor is given as a country average. The complete list of P characterisation factors per country can be found in the latest ReCiPe methodology publication (Huijbregts et al., 2017, Annex S4, p. 162-166).

Annex E: Monetisation of aquatic eutrophication

Introduction

Valuation of aquatic (freshwater and marine water) eutrophication deserves special attention for two reasons. Firstly, estimates of monetary costs of eutrophication vary highly in literature, with values as high as 332 €/kg N (Ahlvik et al. 2012)[32] and 924 €/kg P (Liekens et al., 2010) and as low as 0.01 €/kg N and 0.04 €/kg P (both from Steen, 2015) for marine and freshwater eutrophication respectively. Secondly, aquatic eutrophication is one of the most crucial impacts of agricultural systems since it is a major environmental problem worldwide and fertiliser use is one of its main drivers.

Schematic impact pathway

Eutrophication occurs through business activities that lead to the leaching and discharge of Nitrogen and Phosphorus to marine- and freshwater. This is an output of economic activities. The increase of these nutrients in water bodies leads to algal blooms (aquatic eutrophication) and the loss of water quality. This in turns leads to a loss of aquatic life. These are outcomes of nutrient pollution. Subsequent impacts include damage to biodiversity, economic activities due to the loss of fisheries and aesthetic and recreational value of water. This schematic impact pathway summarises the discussion of the impacts of eutrophication in literature and it is shown in Figure 4 (de Bruyn et al., 2018a and 2018b; EPA, 2015; Steen, 2015).

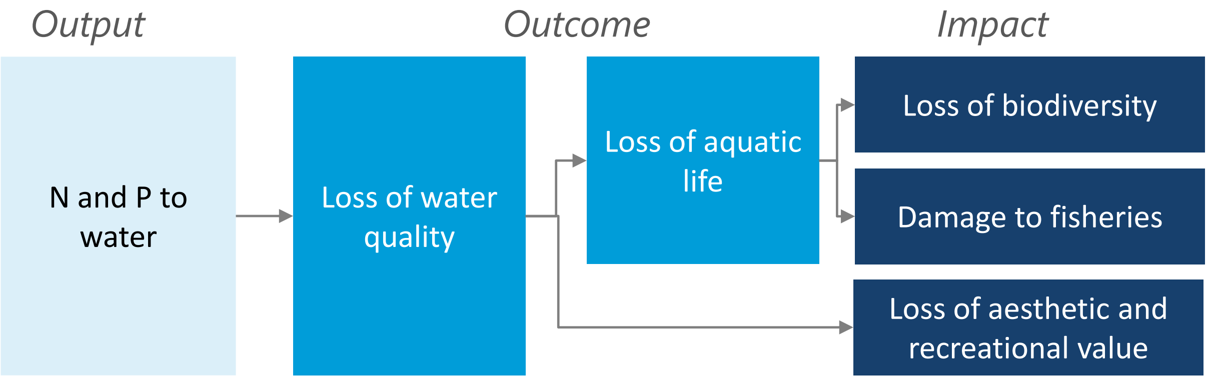

Figure 4: Schematic impact pathway of aquatic eutrophication.

Monetisation approach

As described in the Valuation Framework for True Pricing of Agri-food Products, social and environmental impacts are monetised through remediation cost. For severe, reversible environmental damage this means the cost of restoration, while for damage that cannot reasonably be reversed compensation cost, the cost of compensating stakeholders for the damage received, is considered.[33]

In the case of aquatic eutrophication, **the loss of water quality is considered reversible** since water quality can be restored (outcome level in Figure 4). This means that a restoration (or abatement cost) should be used.

It can be argued that by the time the water quality would be restored, some stakeholders would still have incurred damage if that occurred before restoration is complete (such as biodiversity loss, or lower output

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[32] As quoted in Table 4.3 of BalticSTERN (2013).

[33] If the damage is not severe, which is not the case for eutrophication, the lowest between restoration and compensation cost is taken.

from fisheries – impact level in Figure 4). However, the extent of that damage is uncertain and can only be assessed case to case.

For these reasons, we consider a **restoration** or **abatement cost** for aquatic eutrophication which represents the cost of measures you would need to take to restore water quality.

The monetisation factors are based on the average of the middle range values proposed for use in European cost-benefit analysis of forestry and are derived from a meta-analysis (Prokofieva et al., 2011, p. 49 and 51). Different measures have different costs. The middle range represents measures with medium size opportunity costs like changes in land use practices (e.g., the time of manure spreading and use of catch crops on productive agricultural lands) and changes in animal husbandry practices, such as lower stocking density for Nitrogen and change in livestock holdings and wetland establishment for Phosphorus. No equivalent study for agriculture has been found, but these values do cover abatement measures in agriculture.

The original values from Prokofieva et al. (2011) are shown in Table 12. The resulting monetisation factors are an average of the range provided and have been inflated to the price level of the year 2020.

Table 12: Freshwater and marine eutrophication costs.

Cost eutrophication	Marine (EUR/kg N)	Freshwater P (EUR/kg P)	Source
Abatement cost- middle range (EUR 2011)	5-20	60-300	Prokofieva et al., 2011 (p. 49-51)
Monetisation factors (EUR 2020)	14.07	203	

Limitations

A key limitation of this approach is that, typically, the costs of eutrophication are location-specific and depend on local parameters, such as baseline pollution load in water, the agricultural practices, climate, rainfall, recreation, etc. Abatement cost could also be adjusted depending on pollution targets set by policy representing what water quality is acceptable, and the local cost of abatement measures. The willingness to pay for biodiversity loss and water quality varies with population density and potentially income levels[34]. In absence of more detailed models and local parameters, only default factors for Europe are provided. It is recommended to do further research on adjustment of these factors to derive region-, country- or water basin-specific values.

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[34] Loss of economic output from fisheries represents a global average, which is almost negligible compared to the other components of the monetisation factor.

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Annex F: Monetisation of nitrogen deposition

Annex F.1: Derivation of monetisation factor

In a letter to the Dutch parliament on 24 April 2020, the Dutch cabinet formulated the goal that at least 50% of the hectares with Nitrogen sensitive areas in Natura 2000 areas should be brought below the critical value (Ministerie van Landbouw, Natuur en Voedselkwaliteit, 2020). To realise that goal, a Nitrogen deposition reduction of 255 mol N per hectare in 2030 should be achieved. Planbureau voor de Leefomgeving calculated that measures already taken (in the Netherlands and abroad) should lead to a reduction of approximately 120 mol N per ha per year. In addition, measures expected in the context of the Paris climate agreement should guarantee another 25 mol N per ha per year (van den Born et al., 2020). As a result, additional measures need to be taken that guarantee another 100-120 mol N per ha per year.

It can be argued that the national costs of (additional) measures to meet the deposition limitation target are external costs (as they are typically not paid by those that benefit from the Nitrogen emissions in the first place). For all Nitrogen emissions caused by agriculture that result in higher depositions of Nitrogen in nature areas with Nitrogen levels above that limit, an external cost can be measured. A national average of increased N deposition in Natura 2000 area, as the result of emission of 1 kg of NH_3 or NO_x is calculated based on Van der Maas (2020). Key assumption is that where Van der Maas finds a reduction of deposition from a limitation of emissions, this can symmetrically be applied the other way around: to assume additional deposition from additional emission.[35] Table 13 gives an overview of this.

Table 13: Assumed additional deposition from additional emission in (µmol N/ha/yr) / kg. Source: Van der Maas (2020).

Gas	Emissions source	Assumed additional deposition from additional emission (µmol N/ha/yr) / kg	Assumption
NH_3	Animal husbandry (stables)	7.30	
NH_3	Use of manure	4.60	
NH_3	Other	4.00	When application not specified, use 'old' generic value
NO_x	Agricultural machines and vehicles	0.79	
NO_x	Other	1.50	When application not specified, use 'old' generic value

Proximity of the source of emission to nature-prone areas is a crucial factor in how much Nitrogen is deposited in the areas. Emissions by a farmer close to Natura 2000 areas lead to more deposition of

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[35] Note that in terms of units, mol / kton is identical to µmol / kg.

Nitrogen there. As a result, the external costs per kilogram of Nitrogen emitted are higher than for a farmer further away from such areas. In principle, this effect can be taken into account by including a risk factor, or by micro-modelling deposition. We do not propose this in the scope of this module. Not much information was found on nitrogen deposition outside Europe, but it is recommended to include nitrogen deposition in true price assessment of value chains outside Europe whenever literature shows it to be a material issue.

Calculation basis

Nitrogen emissions to air in the form of ammonia lead to nitrogen deposition (not in the form of N). This is a problem particularly in the Netherlands, where part of the Natura 2000 areas are overloaded by Nitrogen, especially in the sandy area. The Netherlands already needs to take costly measures to limit the emission and reduction of Nitrogen. The key idea of the true price calculation is that every kg of NH_3 or NO_x emitted to the air leads to additional deposition of N on land, including Natura 2000 areas.[36] That subsequently requires scaling up the costly measures to reduce emissions elsewhere. The marginal costs to do so, are then taken as the true costs of NH_3 and NO_x emissions for nitrogen deposition.

The analysis is based on the cost effectiveness of measures discussed in Van den Born et al. (2020). Table 14 orders the measures in Van den Born et al. (2020) by their cost effectiveness – this assumes that measures are enforced over the ‘efficient’ path, starting with the most cost-efficient measures first. In practice each industry will apply different measures with different costs based on specific conditions, but overall, this is a normal assumption in determining marginal abatement costs. The table is used to find the set of measures that needs to be taken in order to meet the national targets. As discussed in the section on background and rationale, this requires an additional deposition-reduction of 100-120 mol N per ha per year. The marginal measure is 'landelijke beëindigingsregeling piekbelasters'. The cost effectiveness of the marginal measure is highlighted in yellow in the table below. This is 3.4 mln Euro/(mol N/ha/yr), or 3.40 Euro/(µmol N/ha/yr).

Table 14: Order of measures in Van den Born et al. (2020), based on their cost effectiveness. The cost-effectiveness of the marginal measure is highlighted in yellow.

No	Measure (cited in Dutch)	Deposition reduction (mol N/ha/yr)	Cumulative deposition-reduction if all measures until this one applied (mol N/ha/yr)	Cost effectiveness last measure (mln Euro / (mol N/ha/yr)
1	Afromen en doorhalen van fosfaatrechten	0	0.0	0.0
2	Subsidiestop ISDE (pellet-kachels en biomassaketels)	0.05	0.1	0.0
3	Vergroten aantal uren weidegang	2.6	2.7	0.2

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[36] A large part of the emitted Nitrogen will not deposit in nature areas. This is excluded from the model. If it deposits in agricultural land, it will even help to reduce the need for fertiliser use for other crops. This is not part of the model to avoid double counting with the calculation of true price gaps of those crops.

4	Verlagen eiwitgehalte veevoer melkvee	30	32.7	0.3
5	Stalmaatregelen melkvee	23	55.7	1.2
6	Handhaving katalysatoren vrachtauto's	2	57.7	2.1
7	Stalmaatregelen varkens	12	69.7	2.3
8	Verlagen eiwitgehalte veevoer varkens	11.5	81.2	3.0
9	Subsidieregeling sanering varkenshouderijen	8.5	89.7	3.3
10	*Landelijke beëindigingsregeling piekbelasters*	*33.7*	*123.4*	*3.4*
11	Gerichte opkoop piekbelasters	9	132.4	4.4
12	Verdunnen mest met water	6.9	139.3	4.6
13	Verlagen eiwitgehalte veevoer pluimvee (leghennen)	10	149.3	4.9
14	Subsidieregeling retrofit binnenvaart	4.2	153.5	6.4
15	Indruk technisch potentieel: aanscherpen eisen 'best beschikbare technieken (BBT)	2.5	156.0	20.0
16	Walstroom zeevaart	0.3	156.3	21.0
17	Realiseerbaar potentieel: specifieke maatwerkaanpak industriele piekbelasters	0.15	156.4	30.0

The following monetisation factors follow from the cost-effectiveness of measures to reduce Nitrogen deposition (Table 15).

Table 15: Monetisation factors for nitrogen deposition in the Netherlands, for all processes that lead to gas emissions with different Nitrogen deposition effects in soil.

Gas	Emissions source	Assumed additional deposition from additional emission (µmol N/ha/yr) / kg in the Netherlands	Costs (Euro) to compensate for the deposition of 1 µmol N/ha/yr in the Netherlands	Contribution to the true price gap per kg gas emission (EUR/kg emitted)
NH_3	Animal husbandry (in stables)	7.30	3.40	24.8
NH_3	Use of manure	4.60	3.40	15.6
NH_3	Other	4.00	3.40	13.6
NO_x	Use of agricultural machines and vehicles	0.79	3.40	2.69
NO_x	Other	1.50	3.40	5.10

Annex F.2: Adjustment of nitrogen deposition monetisation factor for other European countries

For countries other than the Netherlands, local marginal abatement costs should be used. If these are not available, approximations for other EU countries based on adjustments to the Dutch value can be used, as provided in Table 15.

Approach

The base value represents the marginal abatement cost of measures to meet nitrogen deposition policy targets in The Netherlands. To adjust these Netherlands-specific costs to other countries we assume that the abatement cost curve is similar (since no data is available about other abatement cost curves), and we correct for the degree of severity of impacts caused by emissions, in relation with the policy targets. This has two dimensions:

- How much N emitted in that country is likely to be deposited in sensitive nature areas,
- How close those nature areas are with respect to critical N deposition loads established by the EU (see Figure 5).

This reflects in the fact that nitrogen deposition has two thresholds:

- A natural threshold, a critical load based on environmental quality, used as a baseline to measure excess deposition.
- A policy target, a threshold determined in legislation that determines how high excess deposition is allowed to be.

The characterisation factors of the nitrogen deposition method of the Product Environmental Footprint standard of the EU (PEF) and data on the average accumulate exceedance per hectare published by the European Environmental Agency are used for the adjustment.

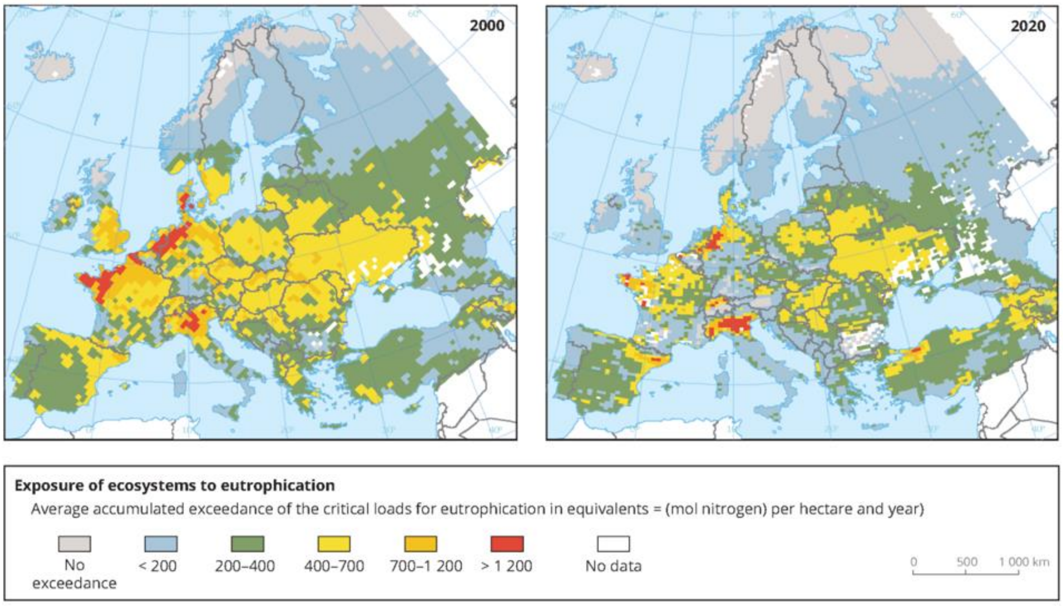

Figure 5: Exposure of ecosystems to risk of eutrophication due to airborne deposition of Nitrogen – area and magnitude of exceedance in 2000 and 2020. Source: European Environmental Agency (EEA, 2019b).

We derive a monetisation factor for a country x using unit value transfer of the Dutch value adjusted to differences in N deposition factors and weighted with the magnitude of exceedance of the critical N threshold in that country.

$$MF_{P,x} = MF_{P,NL} \times \frac{CAE_{P,x}}{CAE_{P,NL}} \times \frac{AAE_x}{AAE_{NL}} \quad (3)$$

Where:

$MF_{P,x}$: Monetisation factor for emissions of pollutant P in country x (NL for Netherlands, which is the starting value).

$CAE_{P,x}$: PEF characterisation factor (country-dependent characterisation factors of Accumulated Exceedance, in mol N-eq / kg of pollutant P) for country x (NL for Netherlands). PEF uses Posch et al. (2008) as a source, where they quantify for the purpose of LCA how much N is deposited in nature sensitive areas (nature areas for which the critical load is exceeded) for 1 kg of NH_3 or NO_2 emitted. This method is explained further in Box 1.

AAE_x: Average Accumulated Exceedance (in mol N-eq/ha/yr) which represents the area-weighted average magnitude of the critical load exceedance[37] of ecosystems in country x (NL for Netherlands) and they are provided by the European Environment Agency[38] (EEA, 2014).

The ratio $CAE_{P,x}/CAE_{P,NL}$ represents how likely an emission of NH_3 or NO_x in country x is to lead to deposition in a sensitive nature area compared to the same emission in the Netherlands, based on environmental transport of pollutants. However, marginal abatement cost does not depend only on how much deposition is caused, but also on how close to the threshold the affected ecosystems are. Therefore, the ratio AAE_x/AAE_{NL} is added, to represent how much ecosystems in country x are affected by nitrogen deposition

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[37] According to the European Environment Agency (EEA) technical report, a critical load is the maximum estimated amount of pollutants, that sensitive environmental elements can be exposed to, without significant harmful effects occurring to them, according to current knowledge (EEA, 2014).

[38] Two types of AAE values are provided, EUNIS for all ecosystems and Natura 2000 for protected ecosystems. These two are similar. We recommend using EUNIS values as it has a more complete dataset.

compared with ecosystems in the Netherlands. Together, the two ratios represent a proxy of how severe the environmental costs caused by an emission of NH_3 or NO_x in country x is compared to an emission of the same gas in the Netherlands.

The method relies on the following assumptions:

- Factors for NO_2 in PEF represent pollution of NO_x and can be used to adjust factors for NO_x in Van den Born et al. (2020). This is in line with the model of Posch et al. (2008), where NO_x is expressed as NO_2.
- Marginal abatement costs are similar in all countries.
- Within a certain interval, marginal abatement costs scale approximately linearly with respect to accumulated exceedance.
- Models of reductions in deposition due to policy measures can be used to estimate increases in deposition due to emissions. Same as in Van den Born et al. (2020) approach, a key assumption is that where Posch et al. (2008) find a reduction of AE from a limitation of emissions, this can symmetrically be applied the other way around: to assume additional AE from additional emission.

Table 16: Nitrogen deposition monetisation factors (EUR2020/kg emitted) for European countries.

	NH_3	*NH_3*	*NH_3*	*NO_x*	*NO_x*
	Animal husbandry (in stables)	**Use of manure**	**Other**	**Use of agricultural machines and vehicles**	**Other**
Netherlands (NL)	25.0	16.0	14.0	2.7	5.1
Albania (AL)	10.7	6.9	6.0	1.0	1.8
Austria (AT)	11.3	7.2	6.3	1.0	1.8
Belarus (BY)	35.0	22.4	19.6	3.2	6.2
Belgium (BE)	0.0	0.0	0.0	0.0	0.0
Bosnia and Herzegovina (BA)	6.6	4.2	3.7	0.7	1.3
Bulgaria (BG)	38.3	24.5	21.5	3.1	5.8
Croatia (HR)	10.8	6.9	6.1	1.5	2.8
Cyprus (CY)	3.8	2.4	2.1	0.2	0.3
Czech Republic (CZ)	14.6	9.3	8.2	1.5	2.9
Denmark (DK)	9.8	6.3	5.5	1.6	3.0
Estonia (EE)	0.9	0.6	0.5	0.1	0.2
Finland (FI)	0.1	0.0	0.0	0.0	0.0
France (FR)	14.1	9.0	7.9	1.4	2.6
Germany (DE)	15.4	9.9	8.6	1.4	2.7
Greece (GR)	7.1	4.5	4.0	0.6	1.0
Hungary (HU)	19.8	12.6	11.1	2.6	4.9

Ireland (IE)	0.2	0.2	0.1	0.0	0.1
Italy (IT)	14.2	9.1	8.0	1.0	2.0
Latvia (LV)	8.8	5.6	4.9	0.8	1.5
Lithuania (LT)	24.0	15.3	13.4	2.3	4.4
Luxemburg	40.7	26.0	22.8	3.5	6.7
Macedonia (MK)	8.6	5.5	4.8	0.7	1.4
Moldova (MD)	8.7	5.6	4.9	1.4	2.7
Norway (NO)	0.0	0.0	0.0	0.0	0.0
Poland (PL)	16.1	10.3	9.0	1.6	3.0
Portugal (PT)	7.6	4.8	4.2	1.2	2.3
Romania (RO)	17.5	11.2	9.8	0.8	1.6
Russia (European part) (RU)	3.5	2.2	2.0	0.3	0.6
Serbia and Montenegro (CS)	11.2	7.2	6.3	1.2	2.3
Slovakia (SK)	22.1	14.1	12.4	2.0	3.9
Slovenia (SI)	2.8	1.8	1.5	0.3	0.5
Spain (ES)	8.3	5.3	4.6	1.1	2.2
Sweden (SE)	0.6	0.4	0.3	0.1	0.2
Switzerland (CH)	41.2	26.4	23.1	3.1	5.8
Turkey (TR)	1.9	1.2	1.1	0.3	0.5
Ukraine (UA)	18.6	11.9	10.4	2.3	4.4
United Kingdom (UK)	0.8	0.5	0.4	0.1	0.2
European average	12.7	8.1	7.1	1.2	2.3

Box 1: PEF approach summary, based on Posch et al. (2008).

The PEF approach is based on the model created by Posch et al. (2008), where atmospheric dispersion and ecosystem sensitivity are accounted for quantifying characterisation factors for terrestrial acidification and eutrophication in LCIA. Deposition of eutrophying emissions is considered in nature sensitive areas in the whole of Europe, and the model measures accumulated exceedance, AE, or deposition in excess of the threshold.

Accumulated exceedance (AE) is defined as the weighted sum of all critical load exceedances within the area of interest (Europe), the weighing factors being the ecosystem areas (Seppala et al, 2006):

$$AE = A_1 \cdot Ex_1 + \cdots + A_n \cdot Ex_n \tag{4}$$

Where:

A_i:	Area of ecosystem i [ha]
Ex_{i}:	Exceedance in ecosystem i as defined above (in mol N-eq/ha/yr)
n:	Number of ecosystems within the area of interest

The PEF characterisation factors for AE (CAE) are country-specific and represent the change in AE, from reduction of emissions of pollutant P in the specific country, with emissions in all other regions unchanged. These CAE are defined for every relevant pollutant P (NH_3, NO_2) as (Seppala et al, 2006):

$$CAE_{P,j} = \frac{\Delta AE_{Europe}^{X-P,j}}{\Delta E_{X-P,j}} \tag{5}$$

Where:

$\Delta AE_{Europe}^{X-P,j}$:	Change in total AE in Europe, after reducing emissions of pollutant P by X (expressed in kt/yr), in the reference year, in country j.
$\Delta E_{X-P,j}$:	Change in emissions of pollutant P in country j, after the reduction of X.

Annex G: Supplementary information on monetisation of human health and ecosystem damage

Introduction

This annex presents the breakdown of global monetisation factors that rely on monetisation of the endpoints of human health and ecosystem damage (biodiversity) taken from ReCiPe 2016. It explains the approach used for deriving them and presents the value choices made for each indicator.

Breakdown of monetisation factors

For several indicators, damage to human health and ecosystems are quantified using ReCiPe 2016 (Huijbregts et al., 2017) and monetised using a standard approach. Formula 6 is the generic formula utilised to calculate the monetisation factor of each indicator.

(6)
$$MF_I = MF_{I,ED} + MF_{I,HHD}$$

Where:

MF_I: Monetisation factor of indicator (EUR/footprint indicator unit)
$MF_{I,ED}$: Monetisation factor of indicator, ecosystems damage (EUR/footprint indicator unit)
$MF_{I,HHD}$: Monetisation factor of indicator, human health damage (EUR/footprint indicator unit)

Ecosystems damage is a component of the monetisation factors for ecotoxicity (terrestrial, marine and freshwater), photochemical oxidant formation, acidification and ozone layer depleting emissions. Human health damage is a component of the monetisation factors for human toxicity, ozone layer depleting emissions, particulate matter formation and photochemical oxidant formation. The resulting monetisation factors and their breakdown are shown in Table 17.

Table 17: Build-up of the 2020 monetisation factors that include human health and ecosystem damage (global values)

Footprint indicator	**Unit**	**Monetisation Factor MF**	**Human health damage MF_{HHD}**	**Ecosystems damage MF_{ED}**
Human toxicity	EUR/DALY	103,048	103,048	-
Terrestrial ecotoxicity	EUR/kg 1,4 DCB-eq emitted to industrial soil	0.00025	-	0.00025
Marine ecotoxicity	EUR/kg 1,4 DB-eq	0.0018	-	0.0018
Freshwater ecotoxicity	EUR/kg 1,4 DB-eq	0.040	-	0.040
PM Formation	EUR/kg $PM_{2.5}$ eq	64.82	64.82	-
POF: damage to ecosystems	EUR/kg NO_x-eq	2.85	-	2.85
POF: damage to human health	EUR/kg NO_x-eq	0.09	0.09	-
Acidification	EUR/kg SO_2-eq	4.68	-	4.68

Ozone Layer Depleting Emissions	EUR/kg CFC 11-eq	56.21	54.72	1.49

Furthermore, with the same method, a monetisation factor can be derived for the ReCiPe midpoint impact of Ionising Radiation equal to $8.76 \cdot 10^{-04}$ EUR/kg Co-60 eq.

The rest of this annex explains the method used to calculate the monetisation factors for the two endpoints.

Ecosystems damage (biodiversity) monetisation

ReCiPe's midpoint to endpoint conversion factors, species density and the valuation of biodiversity loss expressed as PDF.m^2.yr are used to derive the monetisation of ecosystems damage for **ecotoxicity, photochemical oxidant formation** and **acidification** (Formula 7)**:**

$$MF_{I,ED} = \frac{CoF_{I,ED}}{SD_e} \times B_e \qquad (7)$$

Where:

$CoF_{I,ED}$: Midpoint to endpoint conversion factor for indicator (ecosystems damage) (species.yr/footprint indicator unit)

SD_e: Average species density of ecosystem (species/m^2)

B_e: Valuation of biodiversity loss of ecosystem (EUR/PDF.m^2.yr)

The value of ecosystems damage is obtained by multiplying ReCiPe midpoint to endpoint conversion factors for ecosystems damage with the relevant monetary value of biodiversity loss. The endpoint characterisation factors are taken from ReCiPe 2016 (Huijbregts et al., 2017, p.60, p.64 & p. 80). The units of the conversion factors are given in species.year, representing the loss of species during a year (Goedkoop et al., 2009, p.8). These are converted to PDF.m^2.yr by dividing with average species density (see Table 18)[39] with the approach recommended by the ReCiPe method itself.

Average species densities in aquatic ecosystems are given in species/m^3. These have been converted to species/m^2 using average depth of species occurrence in these environments.[40] Terrestrial ecotoxicity, POF and acidification relate to species in terrestrial ecosystems, marine ecotoxicity with species in marine ecosystems and freshwater ecotoxicity with species in freshwater ecosystems.

Table 18: Average species density values for terrestrial, marine, and freshwater ecosystems.

Species ecosystem	Species density - SD_e	Unit	Source
Terrestrial	$1.48 \cdot 10^{-8}$	species/m^2	Huijbregts et al. (2017) p. 79
Marine (in cubic meters)	$3.46 \cdot 10^{-12}$	species/m^3	Huijbregts et al. (2017) p. 79

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[39] For more information on how characterisation factors for loss of species diversity connects to PDF though species density, consult Goedkoop et al. (2009, p.90)

[40] Average marine depth = 200m (Goedkoop et al., 2009, p.11), Average freshwater depth = 7.7 m. Average freshwater depth is calculated utilising OECD data on land cover of inland water in m^2 (OECD, n.d.a) and freshwater renewable resources in m^3 (OECD, n.d.b). Only OECD are considered for the calculation due to a lack of available data regarding non-OECD countries for freshwater resources. Total inland water cover is equal to $1.48 \cdot 10^{12}$ m^2, while total freshwater renewable resources is equal to $1.14 \cdot 10^{13}$ m^3.

Marine (in square meters)	$6.92 \cdot 10^{-10}$	species/m^2	Own calculations
Freshwater (in cubic meters)	$7.89 \cdot 10^{-10}$	species/m^3	Huijbregts et al. (2017) p. 79
Freshwater (in square meters)	$6.09 \cdot 10^{-9}$	species/m^2	Own calculations

There are multiple monetary values of biodiversity loss applied in this module, depending on the ecosystem where the loss takes place (i.e., terrestrial, marine, or freshwater). Table 19 provides an overview of the different values used. These values represent the median annual value of ecosystem services (for more background on these values, see 7.3.2 Ecosystem damage valuation (biodiversity) in the main report).

Table 19: Biodiversity loss valuation for indicators that include ecosystems damage in their monetisation factor (in EUR$_{2020}$/PDF.m^2.yr)

Indicator	**Biodiversity loss valuation - B$_e$**	**Description**	**Source**
Terrestrial ecotoxicity	0.33	Global value terrestrial ecosystems	de Groot et al. (2012); OECD (n.d.a)
Marine ecotoxicity	0.012	Global value marine ecosystems	de Groot et al. (2012); Goedkoop et al. (2009)
Freshwater ecotoxicity	0.35	Global value freshwater ecosystems	de Groot et al. (2012); OECD (n.d.b)
Photochemical Oxidant Formation	0.33	Global value terrestrial ecosystems	de Groot et al. (2012); OECD (n.d.a)
Acidification	0.33	Global value terrestrial ecosystems	de Groot et al. (2012); OECD (n.d.a)

For ozone layer depleting emissions, the monetisation of ecosystems damage is taken directly from CE Delft. The cost of ecosystems is equal to 1.49 EUR$_{2020}$/kg CFC 11-eq and corresponds to the cost of “capital and land” as included in CE Delft (1.25 EUR$_{2008}$/kg CFC 11-eq from de Bruyn et al. (2010), Table 20), since it is stated in CE Delft that an identical approach is followed in the latest version (de Bruyn et al., 2018a, p. 87).

Human health damage monetisation

Formula 8 is used to derive the monetisation of human health damage for particulate matter formation, photochemical oxidant formation and ozone layer depleting emissions:

$$MF_{I,HHD} = CoF_{I,HHD} \times HH \tag{8}$$

Where:

$CoF_{I,HHD}$: Midpoint to endpoint conversion factor for indicator (human health) (year/footprint indicator unit)[41]

HH: Valuation of human health (EUR/DALY)

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[41] The unit ‘*year*’ in ReCiPe endpoint factors is equal to 1 DALY.

The value of human health damage is obtained by multiplying ReCiPe midpoint to endpoint conversion factors for human health damage with the monetary value of a DALY. The conversion factors are taken from ReCiPe 2016 (Huijbregts et al., 2017, p. 43, p. 54 & p. 59). The value of human health in this module is a DALY value of EUR 103,048 at 2020 price level, as described in section 7.3.1. This value is applied to all human health related indicators. For the footprint indicator **Human toxicity**, which is measured in DALY, the value of human health is directly used as a monetisation factor.

No regional adjustment of human health valuation

An important consideration is whether a regional adjustment of the value of human health should be applied, to reflect difference in willingness-to-pay by people in countries with different income and living costs. While both options can be defended, it is decided for the time being not to apply a regional adjustment to the DALY value used. Since this is a normative choice, we suggest that this choice is further discussed with experts and stakeholders in the field. The original value from OECD includes values from different locations and years, and for comparability purposes it is already expressed in the original source in 2005 US dollars using the PPP adjusted exchange rate.

Annex H: Accounting for regional effects of air pollution: acidification, particulate matter formation and photochemical oxidant formation

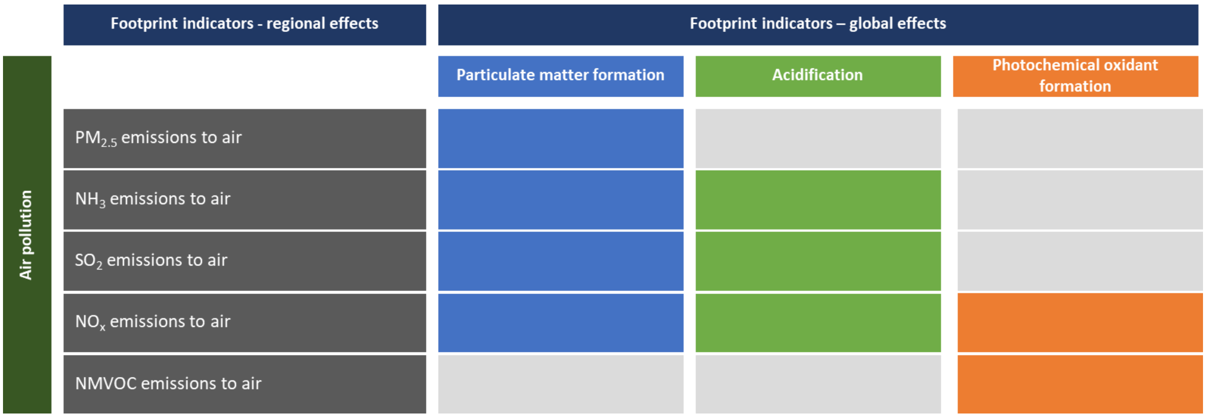
Introduction

This annex provides an approach to account for the regional effects of particulate matter (PM) formation, photochemical oxidant formation (POF) and acidification. It provides details only for the elements that change compared to the method that accounts for the average global effects (as presented in the main text).

The indicators for the other impacts (ozone layer depletion, nitrogen deposition, toxic emissions and eutrophication) remain unchanged. For these indicators, please refer to the main text for the modelling and valuation approach.

Footprint indicators

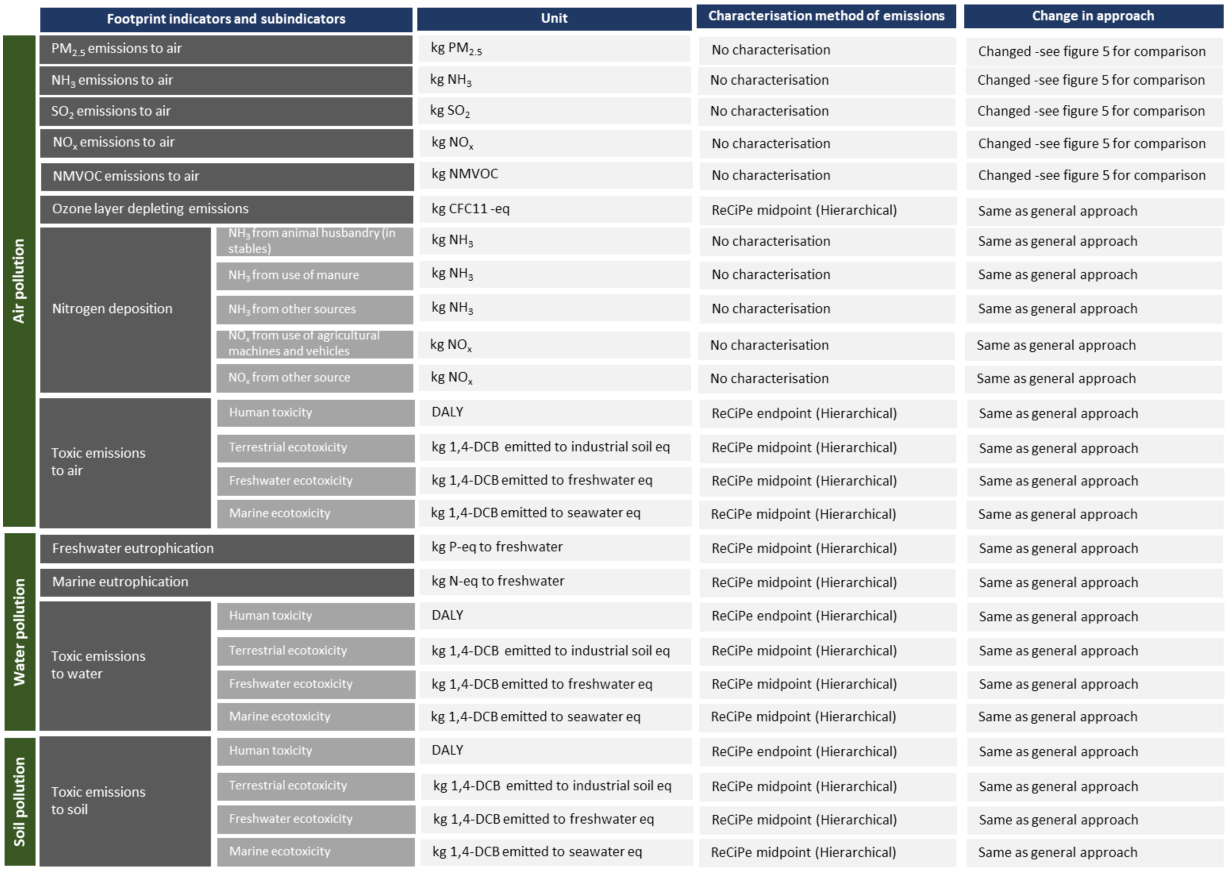
The footprint indicators at midpoint (PM formation, POF and acidification) are replaced by five footprint indicators at pollutant level: $PM_{2.5}$, NH_3, SO_2, NO_x and NMVOC emissions to air (Figure 6**Error! Reference source not found.Error! Reference source not found.**). These pollutant-level indicators capture the regional effects of the different pollutants on PM formation, POF and acidification.



	Footprint indicators - regional effects	Footprint indicators – global effects		
		Particulate matter formation	Acidification	Photochemical oxidant formation
Air pollution	$PM_{2.5}$ emissions to air	🟦		
	NH_3 emissions to air	🟦	🟩	
	SO_2 emissions to air	🟦	🟩	
	NO_x emissions to air	🟦	🟩	🟧
	NMVOC emissions to air			🟧

Figure 6: Relation between indicators, that account for the regional effects of PM formation, POF and acidification, and the indicators that account for the average global effects only.

Figure 7 provides a list of all footprint indicators (for air, soil and water pollution)**Error! Reference source not found.**, including those that account for the regional effects of PM formation, POF and acidification, as well as those that remain unchanged.



	Footprint indicators and subindicators		Unit	Characterisation method of emissions	Change in approach
Air pollution	$PM_{2.5}$ emissions to air		kg $PM_{2.5}$	No characterisation	Changed -see figure 5 for comparison
	NH_3 emissions to air		kg NH_3	No characterisation	Changed -see figure 5 for comparison
	SO_2 emissions to air		kg SO_2	No characterisation	Changed -see figure 5 for comparison
	NO_x emissions to air		kg NO_x	No characterisation	Changed -see figure 5 for comparison
	NMVOC emissions to air		kg NMVOC	No characterisation	Changed -see figure 5 for comparison
	Ozone layer depleting emissions		kg CFC11 -eq	ReCiPe midpoint (Hierarchical)	Same as general approach
	Nitrogen deposition	NH_3 from animal husbandry (in stables)	kg NH_3	No characterisation	Same as general approach
		NH_3 from use of manure	kg NH_3	No characterisation	Same as general approach
		NH_3 from other sources	kg NH_3	No characterisation	Same as general approach
		NO_x from use of agricultural machines and vehicles	kg NO_x	No characterisation	Same as general approach
		NO_x from other source	kg NO_x	No characterisation	Same as general approach
	Toxic emissions to air	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)	Same as general approach
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)	Same as general approach
Water pollution	Freshwater eutrophication		kg P-eq to freshwater	ReCiPe midpoint (Hierarchical)	Same as general approach
	Marine eutrophication		kg N-eq to freshwater	ReCiPe midpoint (Hierarchical)	Same as general approach
	Toxic emissions to water	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)	Same as general approach
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)	Same as general approach
Soil pollution	Toxic emissions to soil	Human toxicity	DALY	ReCiPe endpoint (Hierarchical)	Same as general approach
		Terrestrial ecotoxicity	kg 1,4-DCB emitted to industrial soil eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Freshwater ecotoxicity	kg 1,4-DCB emitted to freshwater eq	ReCiPe midpoint (Hierarchical)	Same as general approach
		Marine ecotoxicity	kg 1,4-DCB emitted to seawater eq	ReCiPe midpoint (Hierarchical)	Same as general approach

Figure 7: Overview of all footprint indicators and sub-indicators for each impact category when accounting for regional effects of PM formation, POF and acidification.

Five **air pollution** indicators replace the indicators particulate matter formation, photochemical oxidant formation and acidification:

- **$PM_{2.5}$ emissions to air** measures the emissions of $PM_{2.5}$ aerosols in the air. $PM_{2.5}$ emissions cause human health problems as they reach the upper part of the airways and lungs when inhaled (Huijbregts et al., 2017).
- **NH_3 emissions to air** measures the emissions of NH_3 pollutants in the air. NH_3 emissions have acidifying effects, leading to acid precipitation which increases the level of acidity in the soil that causes shifts in a species occurrence (Huijbregts et al., 2017). They also constitute secondary $PM_{2.5}$ aerosols causing the same effects in human health as the primary aerosol.
- **SO_2 emissions to air** measures the emissions of SO_2 pollutants in the air. SO_2 emission have acidifying effects, leading to the same effects described above. They also constitute secondary $PM_{2.5}$ aerosols causing the same effects in human health as the primary aerosol.
- **NO_x emissions to air** measures the emissions of NO_x pollutants in the air. NO_x emissions have acidifying effects, leading to the same effects described above. They also constitute secondary $PM_{2.5}$ aerosols causing the same effects in human health as the primary aerosol. Finally, NO_x emissions can absorb light that causes a photochemical reaction which leads to ozone formation. Ozone is not directly emitted to the atmosphere, but it is a health hazard to humans because it can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of respiratory distress in humans, such as asthma and Chronic Obstructive Pulmonary Diseases (COPD). Additionally, ozone can have a negative impact on vegetation, including a

reduction of growth and seed production, an acceleration of leaf senescence and a reduced ability to withstand stressors (Huijbregts et al., 2017).

NMVOC emissions to air measures the emissions of NMVOC pollutants in the air. NMVOC emissions can absorb light that causes a photochemical reaction which leads to ozone formation, causing the same effects to humans and ecosystems described above.

In the remaining part of this annex, the word indicators refers to the five indicators at pollutant level, unless specifically stated otherwise.

Modelling approach and data requirements

The indicators can be quantified as kg of pollutants emitted to the air during the different processes in the life cycle of the product under assessment. These can be taken from the inventory of an LCA, before characterisation is applied with an LCIA method, such as ReCiPe. If an LCA is not available many emissions of pollutants to air at farm level can be estimated based on the use of agro-inputs on farm level, as described in Section 6.8.

Monetisation

Monetisation factors

An overview of global and Dutch monetisation factors for the indicators is presented in Table 20. All values are expressed at 2020 price level. Values from original sources are inflated and converted, if needed, to euros to obtain the 2020 monetisation factors.

Table 20: Monetisation factors for the indicators. NL = Netherlands. Sources: (1) Biausque (2012); (2) Huijbregts et al. (2017); (3) de Groot et al. (2012); (4) OECD (n.d.a.); (5) de Bruyn et al. (2018a).

Indicator	Unit	Value – Global	Value – NL	Sources
$PM_{2.5}$ emissions to air	EUR/kg $PM_{2.5}$	64.84	133.96	(1)(2)
NH_3 emissions to air	EUR/kg NH_3	24.52	82.70	(1)(2)(3)(4)
SO_2 emissions to air	EUR/kg SO_2	23.56	20.40	(1)(2)(3)(4)
NO_x emissions to air	EUR/kg NO_x	11.87	37.21	(1)(2)(3)(4)(5)
NMVOC emissions to air	EUR/kg NMVOC	0.83	4.70	(1)(2)(3)(4)(5)

Regional adjustment of monetisation factors

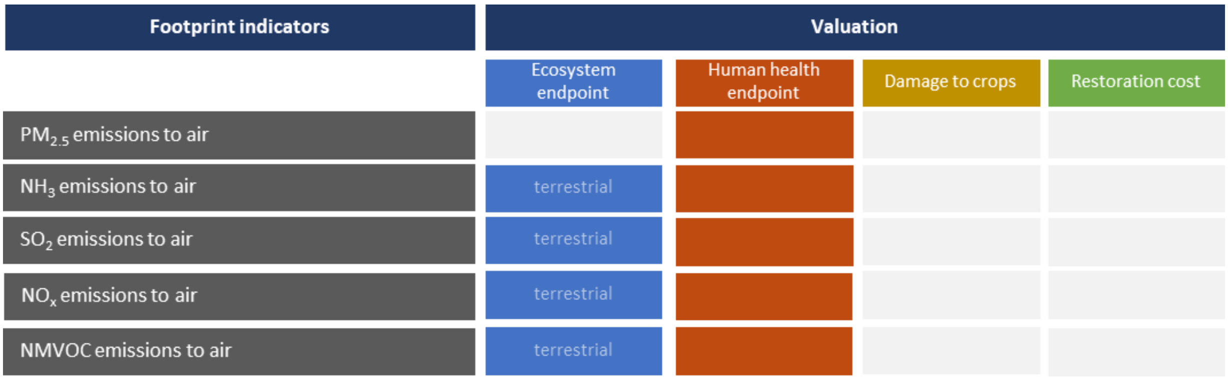
Global average and Netherlands specific monetisation factors are provided. Factors specific to other countries can be derived by utilising country-specific endpoint factors for human health and ecosystem damage, available from ReCiPe 2016 (Huijbregts et al., 2017). The approach to obtain these country-specific factors is explained in the following sections.

Valuation approach

The monetisation factors are based on damage cost (compensation cost), looking at human health damage, ecosystems damage, or both, following the same endpoint valuation as described in sections 7.2 and 7.3. The difference between the two approaches is that this approach uses ReCiPe 2016 endpoint characterisation factors to derive the monetisation factors, instead of midpoint to endpoint conversion factors (Huijbregts et al., 2017), together with standard damage cost factors for human health and ecosystem damage units.

Human health damage relating to ozone formation from NO_x and NMVOC emissions in the Netherlands is not quantified and valued using ReCiPe and OECD (Biausque, 2012). A different approach is taken, following CE Delft (de Bruyn et al., 2018a). They argue that human health models of emission sources that lead to POF often underestimate the impact and they developed a more sophisticated model. This is not available for other countries. Therefore, for the Netherlands, the value for human health developed in that study is used instead. Consequently, monetisation factors related to human health damage are included in the indicators NO_x and NMVOC emissions to air: 19.61 EUR/kg NO_x and 2.20 EUR/kg NMVOC, respectively, for 2020 prices (de Bruyn et al., 2018a, Table 33 p. 106, central values).[42] This might be considered as a limitation of the method, since CE Delft (de Bruyn et al., 2018a; de Bruyn et al., 2018b) uses a lower DALY value than OECD (Biausque, 2012). However, the CE Delft method provides more in-depth results, concerning population data and the interplay between emitted pollutants and their effect on human health. The level to which these nuances offset the lower DALY value is not clear yet.

Figure 8 below summarises the valuation approach used for each indicator.



Footprint indicators	Valuation			
	Ecosystem endpoint	Human health endpoint	Damage to crops	Restoration cost
$PM_{2.5}$ emissions to air		🟧		
NH_3 emissions to air	terrestrial	🟧		
SO_2 emissions to air	terrestrial	🟧		
NO_x emissions to air	terrestrial	🟧		
NMVOC emissions to air	terrestrial	🟧		

Figure 8: Valuation approach used for each indicator.

The endpoint of **human health** is used implicitly for all five indicators. It is based on valuation of a DALY. The monetary value of a DALY is the main element of human health valuation in this method and is equal to EUR 103,048 at 2020 price level (see section 7.3.1). The value is not adjusted for countries with different income and living costs and can be used globally. More information on this can be found in Annex G: Supplementary information on monetisation of human health and ecosystem damage.

The endpoint of **ecosystems damage** is used for the valuation of all indicators, with the exception of $PM_{2.5}$ emissions to air, since these emissions do not have any effect in ecosystems, following the ReCipe methodology (Huijbregts et al., 2017). Damage to ecosystems in this module is valued in terms of impacts on **biodiversity**.[43] Impacts on biodiversity of each indicator are measured in PDF.m^2.yr and modelled using ReCiPe endpoint factors (Huijbregts et al. 2017).

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[42] Inflation from original year (2015) is applied to bring the values in 2020 prices – cumulative inflation: 1.05 (World Bank, n.d.)

[43] For more information on the relationship between ecosystems, ecosystem services and biodiversity consult the impact-specific module **Land use, Land use change, Biodiversity and Ecosystems Services** (Galgani et al. 2021c).

Breakdown of monetisation factors

The monetisation factor of each indicator in Table 20 is the sum of two parts: damage to human health and damage to ecosystems (Formula 6).

$$MF_I = MF_{I,ED} + MF_{I,HHD} \quad (6)$$

Where

MF_I:	Monetisation factor of indicator I (EUR/kg pollutant)
$MF_{I,ED}$:	Monetisation factor of indicator I, ecosystems damage (EUR/kg pollutant)
$MF_{I,HHD}$:	Monetisation factor of indicator I, human health damage (EUR/kg pollutant)

Figure 6 indicates if the monetisation factor of a specific indicator consists of both parts of formula 6, or only one. Damage to human health and to ecosystems are monetised using a standard approach (see below). The resulting monetisation factors are multiplied with their corresponding footprint indicator (quantified in kg of pollutant).

Table 21: Build-up of the 2020 monetisation factors (Dutch values)

Footprint indicator	Unit	Monetisation Factor MF_I	Effect	Human health damage $MF_{I,HHD}$	Ecosystems damage $MF_{I,ED}$
$PM_{2.5}$ emissions to air	EUR/kg $PM_{2.5}$	133.96	Particulate matter formation	133.96	-
NH_3 emissions to air	EUR/kg NH_3	82.70	Particulate matter formation	72.10	-
			Acidification	-	10.60
SO_2 emissions to air	EUR/kg SO_2	20.40	Particulate matter formation	14.40	-
			Acidification	-	6.00
NO_x emissions to air	EUR/kg NO_x	37.21	Particulate matter formation	14.42	-
			Acidification	-	2.53
			Photochemical oxidant formation	19.61	0.65
NMVOC emissions to air	EUR/kg NMVOC	4.70	Photochemical oxidant formation	2.20	2.50

Ecosystems damage valuation (biodiversity)

ReCiPe’s endpoint characterisation factors, species density and the valuation of biodiversity loss expressed as PDF.m^2.yr are used to monetise ecosystems damage (ED) (Formula 7)**:**

$$MF_{I,ED} = \frac{\sum_m EF_{I,ED,m}}{SD_e} \times B_e \quad (7)$$

Where

m: Midpoint effect connected to pollutant that corresponds to indicator I
$EF_{I,ED,m}$: Endpoint characterisation factor of pollutant that corresponds to indicator I and relates to midpoint effect m (ecosystems damage) (species.yr/kg pollutant)
SD_e: Average species density of ecosystem (species/m^2)
B_e: Valuation of biodiversity loss of ecosystem (EUR/PDF.m^2.yr)

For example, as shown in Figure 6**Error! Reference source not found.**, the indicator (I) NH_3 emissions to air is connected to the midpoint effects (m) of particulate matter formation and acidification. Out of these midpoint effects only acidification leads to damage to ecosystems (Table 17). For the Netherlands, country-specific endpoint characterisation factor for ecosystem damage $EF_{I,ED}$ due to acidifying NH_3 emissions is provided by Recipe and is equal to 4.78E-07 species.yr/kg NH_3 (Huijbregts et al. 2017, Table S3.2., p. 151). This value is converted to PDF.m^2.yr by dividing with average (terrestrial) species density, SD_e, (see Table 18) and then multiplied with the global value for biodiversity loss of (terrestrial) ecosystem, B_e, (see Table 19) resulting in a monetisation factor for ecosystems damage, $MF_{I,ED}$, equal to 10.60 EUR/kg NH_3.

Human health damage valuation

Formula 8 is used to derive the monetisation of human health damage for particulate matter formation, photochemical oxidant formation and ozone layer depleting emissions:

$$MF_{I,HHD} = \sum_m EF_{I,HH,m} \times HH \tag{8}$$

Where
m: Midpoint effect connected to pollutant that corresponds to indicator I
$EF_{I,HHD}$: Endpoint characterisation factor of pollutant that corresponds to indicator I and relates to midpoint effect m (human health) (year/kg pollutant)[44]
HH: Valuation of human health (EUR/DALY)

For example, as shown in Figure 6**Error! Reference source not found.**, the indicator (I) NH_3 emissions to air is connected to the midpoint effects (m) of particulate matter formation and acidification. Out of these midpoint effects particulate matter formation leads to damage to human health (Table 17). For the Netherlands, region-specific endpoint characterisation factor for human health $EF_{I,HH}$ due to fine dust formation from NH_3 emissions is provided by Recipe and is equal to 7.0E-04 year/kg NH_3 (Huijbregts et al. 2017, Table S3.2., p. 131). This value is then multiplied with the with the monetary value of a DALY, resulting in a monetisation factor for human health damage, $MF_{I,HH}$, equal to 72.10 EUR/kg NH_3.

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[44] The unit '*year*' in ReCiPe endpoint factors is equal to 1 DALY.

Glossary

Potentially Disappeared Fractions (PDF)	The relative change in vascular plant and other taxa species richness compared with the semi-natural ecosystem that would arise without human interference
Mean Species Abundance (MSA)	The relative abundance of originally occurring species compared with the undisturbed ecosystem
Disability Adjusted Life Year (DALY)	The sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability. One DALY represents the loss of the equivalent of one year of full health. Using DALYs, the burden of diseases that cause early death but little disability (e.g., drowning or measles) can be compared to that of diseases that do not cause death but do cause disability (e.g., cataract causing blindness).