Sustainability **2010**, *2*, 963-979; doi:10.3390/su2040963

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

The Influence of Nutrients and Non-CO_2 Greenhouse Gas Emissions on the Ecological Footprint of Products

Marlia M. Hanafiah [1,2,]*, Mark A.J. Huijbregts [1] and A. Jan Hendriks [1]

[1] Department of Environmental Science, Institute for Water and Wetland Research, Faculty of Science, Radboud University Nijmegen, 6500 GL Nijmegen, The Netherlands; E-Mails: M.Huijbregts@science.ru.nl (M.A.J.H.); A.J.Hendriks@science.ru.nl (A.J.H.)

[2] Department of Environmental Science, School of Environmental & Natural Resource Sciences, Faculty of Science, National University of Malaysia, 43600 UKM Bangi, Selangor, Malaysia

* Author to whom correspondence should be addressed; E-Mail: M.Hanafiah@science.ru.nl; Tel.: +31-243-652-060; Fax: +31-243-553-450.

Received: 12 February 2010; in revised form: 12 March 2010 / Accepted: 29 March 2010 / Published: 7 April 2010

Abstract: The ecological footprint (EF) commonly neglects the influence of other stressors than land use and CO_2 emissions on the land area required for human activities. This study analyzes the relevancy of including nutrients and non-CO_2 greenhouse gases in the EF assessment of products. The analysis was based on environmental information for 1,925 goods and services. Our findings suggest that within specific product categories, *i.e.*, waste treatment processes, bio-based energy, agricultural products and chemicals, adding non-CO_2 greenhouse gases and nutrient emissions can have a dominant influence on the EF results.

Keywords: ecological footprint; non-CO_2 greenhouse gases; nutrient emissions; products

1. Introduction

The Ecological Footprint (EF) is widely used as an indicator for environmental performance [1]. The EF has proven to be one of the most successful devices for communicating the concept of environmental sustainability. The EF concept, as introduced by Rees [2] and further developed by Rees and Wackernagel [3] and Wackernagel and Rees [4], is an accounting tool for the resource consumption and waste assimilation of a defined human population in terms of productive land area. This productivity refers to the amount of biomass production required to renew the biotic resources used by humans and to absorb CO_2 emissions from energy use [5,6]. Productivity area is measured in global hectares, which are measured from actual hectares by weighting with yield factors and equivalence factors which can be compared to the biocapacity of the earth to assess potential ecological overshoot by human activities [7]. The EF has been applied to evaluate impacts of human activities on the environment for different scales, such as on the international level [1], national level [8-12], sub-national level [13-16] and product level [17]. Note that if the focus is on individual products, a biocapacity benchmark to assess ecological overshoot is not straightforward anymore.

In the life cycle assessment (LCA) of goods and services, the EF methodology can also be used to aggregate various types of land use and CO_2 emissions into a single indicator score. Recently, Huijbregts *et al.* [17] calculated the EF for a large number of products including direct land use, nuclear energy use and CO_2 emissions. These EF-scores represent the traditional LCA approach, *i.e.*, multiple-counting of ecological footprints for intermediate products in supply chains. Adding these producer's footprints to other producers' footprints would lead to double-counting. For implementation in a consumer-based approach, only final consumer products should be included in the footprint calculations. Avoiding double-counting could also follow a shared producer and consumer responsibility approach, for instance based on value added, as pointed out by Lenzen *et al.* [18].

An advantage of the EF is that the methodology avoids complex modeling of the environmental cause-effect chain and the indicator score (area of productive land required) is rather easy to understand [14,19]. The EF methodology has, however, also been criticized for a number of reasons, such as the inclusion of only a limited number of stressors [20,21], the focus on impacts on bioproductivity instead of biodiversity [6,22], problems with the selection of appropriate spatial boundaries [23], prejudice against international trade [24,25], and limited use for policy-making [26-29]. For a more in depth discussion of research needs to further enhance the EF method, the reader is referred to Kitzes *et al.* [30].

This paper addresses one aspect of this list of critical points, by expanding the list of stressors that can be taken into account in the EF calculation. More specifically, the goal of this paper is to assess the importance of non-CO_2 greenhouse gases and nutrient emissions in the EF calculation of products. We selected nutrients and non-CO_2 greenhouse gases as they can be (indirectly) linked to the bioproductivity approach and are released to the environment in relatively large quantities. A more complete picture of the EF may change the environmental ranking of products and may give new insights in the environmental improvement potential of supply chains. Although other stressors, such as heavy metals and persistent organic pollutants, are also candidates to include in the EF, we did not have the data to do so from a bioproductivity point of view.

We will show the influence of these methodological changes for 1,925 goods and services, subdivided into 19 product groups. The paper starts with an explanation of the original method applied to calculate the EF of products and the modifications introduced to add non-CO_2 greenhouse gas emissions and nutrient emissions to the EF. We will show the relative contribution of the nutrient and non-CO_2 greenhouse gas emissions to the EF of the products included as well as discuss the implications of our findings for the EF methodology.

2. Methods

In our assessment, the following four "stressor" categories were considered: (1) 27 direct land use types (Appendix A), (2) CO_2 emissions, (3) 31 non-CO_2 greenhouse gas emissions (Appendix B), and (4) nutrient emissions, which include nitrogen (N) and phosphorus (P) emissions to land and water as well as nitrogen oxides (NOx), ammonia (NH_3), nitrate (NO^{3-}) and P emissions to air (Appendix C). The original EF method (stressor categories 1 and 2) was based on Wackernagel and Rees [4] and Huijbregts *et al.* [17]. The original and modified EF scores were calculated using the Ecoinvent database v2.0 [31].

2.1. Original EF Method

In the context of life cycle assessment, a product's EF has been defined as the sum of time-integrated direct land use (EF_{direct}) and indirect land use, caused by CO_2 emissions from fossil-fuel combustion and cement production (EF_{CO2}) [17].

$$EF_{original} = EF_{direct} + EF_{CO_2} \tag{1}$$

Six main high intensity land use types were classified; forest area (for timber and wood), arable land (for food, feed, *etc.*), pasture land (for animal grazing), urban land (for living, construction activities, *etc.*), land required to produce hydropower and marine area (for fish production). Direct land use was calculated by multiplying the area by land use type p (m^2 yr) with its equivalence factors (dimensionless):

$$EF_{direct} = \sum_{p} A_p \cdot EqF_p \tag{2}$$

The equivalence factors (EqF) based on Wackernagel *et al.* [7] were applied in our study (Table 1). EqF is used to convert world-average land use of a specific type, such as forest or pasture, to global hectares. Wackernagel *et al.* [7] defined the global hectares as hectares with world-average productivity for all of the bioproductive areas in the world. A high EqF represents high productivity land, such as cropland, while pastures have a low EqF. Wiedmann and Lenzen [32] argued that using actual yields for the calculation of land-use requirements in combination with global average equivalence factors for assessing bioproductivity is not consistent. However, in the context of life cycle assessment of products, equivalence factors can be seen as generic factors to aggregate different types of land use in terms of "bioproductive area" [17]. In life cycle assessment, aggregation of different types of stressors is generally done with average factors without further regional differentiation [33]. Note that the use of generic equivalence factors implies that our results are not directly comparable with spatially explicit ecological footprint studies.

The EqF for more detailed land use types as specified in the Ecoinvent database v2.0 can be found in Appendix A [7,31].

The productive area (m^2 yr) required to sequester fossil CO_2 emissions was obtained by:

$$EF_{CO2} = M_{CO2} \cdot \frac{1 - F_{CO2}}{S_{CO2}} \cdot EqF_f \tag{3}$$

where M_{CO2} is the product-specific emission of CO_2 (kg CO_2), F_{CO2} is the fraction of CO_2 absorbed by oceans (dimensionless), S_{CO2} is the sequestration rate of CO_2 by biomass (kg CO_2 m^{-2} yr^{-1}) and EqF_f is the equivalence factor of forests (dimensionless).

We excluded nuclear energy in the EF calculations, as there are no suitable methods available to deal with nuclear energy in the EF calculation [30].

Table 1. Parameters used for the EF calculation.

Parameter	Abbrev.	Unit	Value	References
Equivalence factor of forest area	EqF_f	-	1.4	Wackernagel *et al.* [7]
Equivalence factor of urban area	EqF_u	-	2.2	Wackernagel *et al.* [7]
Equivalence factor of arable land	EqF_a	-	2.2	Wackernagel *et al.* [7]
Equivalence factor of pasture area	EqF_p	-	0.5	Wackernagel *et al.* [7]
Equivalence factor of area required for hydropower	EqF_h	-	1	Wackernagel *et al.* [7]
Equivalence factor of marine area	EqF_m	-	0.4	Wackernagel *et al.* [7]
Fraction of CO_2 absorbed by oceans	F_{CO2}	-	0.3	Wackernagel *et al.* [7]
Sequestration rate of CO_2 by biomass	S_{CO2}	kg CO_2 m^{-2} yr^{-1}	0.4	Wackernagel *et al.* [7]
Phosphorus uptake in agricultural soils	U_P	kg P m^{-2} yr^{-1}	0.0009	Antikainen and Haapanen [36]
Nitrogen uptake in agricultural soils	U_N	Kg N m^{-2} yr^{-1}	0.0062	Antikainen and Haapanen [36]
Denitrification rate in agricultural soils	D_N	kg N m^{-2} yr^{-1}	0.0065	Hofstra and Bouwman [37]

2.2. Modified EF Method

Here, we modify the basic EF equation to include the other pollutants as well. The summed EF ($EF_{modified}$) was calculated by:

$$EF_{modified} = EF_{direct} + EF_{CO_2} + EF_{ghg} + EF_{nutrient} \tag{4}$$

where EF_{ghg} is the product-specific EF of non-CO_2 greenhouse gases (m^2 yr) and $EF_{nutrient}$ is the product-specific EF of nutrient emissions (m^2 yr).

2.2.1. Greenhouse Gas Emissions

To include non-CO_2 greenhouse gases into the EF calculation, global warming potentials (GWPs) for a time horizon of 100 years of greenhouse gases other than CO_2 were used to convert greenhouse gas emissions into CO_2 equivalents [34]. Using GWPs as weighting factors, the "artificial" forest required to sequester the amount of additional CO_2 equal to the contribution of non-CO_2 greenhouse gas emissions was derived. The area needed for sequestration was calculated by:

$$EF_{ghg} = \sum_x M_{ghg,x} \cdot \frac{1 - F_{CO2}}{S_{CO2}} \cdot GWP_x \cdot EqF_f \tag{5}$$

where EF_{ghg} is the product-specific EF of indirect land occupation by greenhouse gas emissions excluding CO_2 (m^2 yr), $M_{ghg,x}$ is the product-specific emissions of greenhouse gas x (kg ghg), and GWP_x is the global warming potentials of greenhouse gas x (kg CO_2-equivalents kg^{-1}). The GWP for a time horizon of 100 years of the greenhouse gases included are listed in Appendix B [34,35].

2.2.2. Nutrient Emissions

Nutrient emissions to water (ocean, groundwater and freshwater), industrial soil and air were included by calculating the area required to absorb these emissions [13]. Appendix C lists the emissions that were included in the calculations. We determined how much area is needed to balance nutrient emissions by N and P uptake in plants and denitrification of N in agricultural soils. The EF was calculated separately for N and P. The area required to counterbalance emissions of P and N individually was calculated by:

$$EF_P = \sum_x M_{P,i} \cdot \frac{1}{U_P} \cdot EqF_{agri} \tag{6}$$

$$EF_N = \sum_x M_{N,i} \cdot \frac{1}{U_N + D_N} \cdot EqF_{agri} \tag{7}$$

where EF_P and EF_N are, respectively, the product-specific EF of indirect land occupation by P and N emissions to land, water and air (m^2 yr), $M_{P,i}$ and $M_{N,i}$ are, respectively, the product-specific P and N emissions to compartment i (kg), U_P and U_N are, respectively, the uptake rate of P and N by crops (kg m^{-2} yr^{-1}), D_N is the denitrification rate of N in agricultural soils and EqF_{agri} is the equivalence factor of agricultural soils (dimensionless). N and P uptake rates by crops were set to 62 and 9 kg ha^{-1} yr^{-1}, respectively, based on Antikainen and Haapanen [36]. A typical denitrification rate of 65 kg ha^{-1} yr^{-1} in agricultural soils was derived from Hofstra and Bouwman [37].

The EF concept considers each land area as a single function of use, reflecting the mutually exclusive uses of the bioproductive land. To avoid double counting along the production chains, the same area can be used to compensate for more than one stressor [38]. We assume that if the dominant stressor has been adequately assimilated, then other emissions were assimilated as well. In this study, the additional area required to balance the most dominant nutrient stressor was used in the modified footprint calculations. The EF for nutrients was calculated by:

$$EF_{nutrient} = \max(EF_P, EF_N) \tag{8}$$

where $EF_{nutrient}$ is the product-specific EF of nutrient emissions (m^2 yr). In fact, we assume that all N and P emissions within one supply chain can be compensated by one piece of additional agricultural land and that this land can be either P or N limited. N and P inputs to agricultural soils were not considered as emissions. Based on the fertilizing recommendations for agricultural products, the N and P inputs basically cover the agricultural crop needs [31]. Thus, N and P inputs to agricultural land and subsequent uptake by crops are readily covered in the agricultural supply chain. This implies that for N and P emissions to agricultural soils, additional crop land is only required to counterbalance excess N and P emissions to air and water. In this context, we specifically included net emissions of NH_3, NO_x and NO_3^- released to the air due to the high input of N fertilizers in intensive agriculture. For emissions to water, we included NO_3^- lost from the agricultural soil system by leaching to groundwater and run-off to surface water. P transported from agricultural soil to water *via* soil erosion, leaching and run-off was included as well.

2.3. Product Database

Life cycle inventory data were taken from the Ecoinvent database v2.0 [31]. A total of 1,925 goods and services comprising 19 product groups were considered in the study. The present study includes energy production processes by non-renewable energy sources (oil, natural gas, hard coal and lignite) and renewable energy sources (biomass, wind, solar and hydro), material production (chemicals, building materials, metals, glass, electronics, plastics, agricultural products, and paper and cardboard), transport (goods and passengers), waste management (landfill, incineration, waste water treatment and recycling) and infrastructure. Table 2 lists the product groups and the corresponding number of products included in our analysis.

Table 2. Product groups and number of goods and services included in the analysis as based on Ecoinvent [31].

Product group	Unit	Number of products
Fossil energy [a]	MJ	170
Nuclear energy	MJ	6
Biomass energy	MJ	79
Wind and solar energy	MJ	48
Hydro energy	MJ	31
Building materials [b]	kg	93
Metals	kg	157
Plastics	kg	62
Paper and cardboard	kg	47
Chemicals [c]	kg	450
Glass [d]	kg	12
Electronics	kg	66
Agricultural products [e]	kg	122
Landfill [f]	kg	99
Incineration [g]	kg	69
Waste water	m^3	26
Goods transport	tkm	39
Passengers transport	pkm	20
Infrastructure	unit	329

[a] Oil, natural gas, hard coal and lignite.

[b] Construction materials, insulation materials, mortar and plaster.

[c] Pesticides, mineral fertilizers, washing agents, paintings, inorganics and organics.

[d] Construction and packaging.

[e] Feed production, seed production, animal production and plant production.

[f] Residual material, sanitary landfill, underground deposit, land farming and inert material.

[g] Municipal waste and hazardous waste.

2.4. Data Analysis

First, we analyzed the average relative contribution of direct land use (forestry, crops, pasture, built up, marine area and hydropower) and indirect land use (CO_2, non-CO_2 greenhouse gases and nutrient emissions) for the 19 product groups identified. Second, to assess the influence of non-CO_2 greenhouse gases and nutrients, we calculated the following ratio of the original EF and modified EF per product group ($R_{pollutant}$):

$$R_{pollutant} = \frac{EF_{direct} + EF_{CO2}}{EF_{direct} + EF_{CO2} + EF_{ghg} + EF_{nutrient}} \tag{9}$$

We plotted the median $R_{pollutant}$ together with the 5th, 25th, 75th and 95th percentiles per product group.

3. Results

The relative contributions to the EF of direct land use, CO_2, non-CO_2 greenhouse gases and nutrient emissions to water, land and air are illustrated in Figure 1. The EF of all of the product groups is dominated by CO_2 emissions, except for biomass energy, agricultural products, paper and cardboards, and landfill. These product groups are dominated by direct land use with an average contribution between 49% and 59%. Regarding non-CO_2 greenhouse gases, the average relative contribution is 3% to 16%. N or P emissions to water contribute on average less than 5% for most product categories, except for landfill, waste water treatment, incineration and agricultural products, in which the average contribution is as great as 34%. N or P emissions to land have a small contribution for all product categories involved with an average contribution less than 3%. N or P emissions to air add between 2% and 15% to the total EF, with the highest average contribution reported for the production of metals. We provide an alternative calculation for the relative contribution to the EF by using the summed EF instead of the maximum EF for nutrient emissions. A relatively large difference between the maximum and summed EF for nutrient emissions is reported for agricultural products. For the maximum EF, the average share of N and P emissions to water is lower compared to the summed EF (22% *versus* 26%). Results of the summed EF can be found in Appendix D (Figure A1).

Figure 2 shows the ratios of the original and modified EF scores per product group ($R_{pollutant}$). For most product groups, the median $R_{pollutant}$ is larger than 0.8, indicating that nutrients and non-CO_2 greenhouse gas emissions contribute less than 20% to the EF scores. Contribution of nutrients and non-CO_2 greenhouse gases is, however, much higher for waste water treatment and landfill, for which they typically contribute 38% and 57%, respectively. Figure 2 also indicates that 5% of the processes within waste treatment categories (incineration, landfill and waste water treatment), biomass energy, metals, chemicals and agricultural products have an R smaller than 0.5. This implies that for 5% of the goods and services included in these product groups, the EF scores are more than 50% determined by nutrients and non-CO_2 greenhouse gases. We also calculated the ratios of the original and modified EF for the pollutants only, *i.e.*, "CO_2" *versus* "CO_2, non-CO_2 greenhouse gases and nutrient emissions". Box plots of these pollutants ratios can be found in Appendix D (Figure A2).

Figure 1. Relative contribution of direct land use, CO_2 emissions, non-CO_2 greenhouse gases, N or P emissions to water (include nitrate, nitrite, phosphate), N or P emissions land, and N or P emissions to air (include ammonia, nitrogen oxides, nitrate and phosphorus) to the EF for 19 product groups.

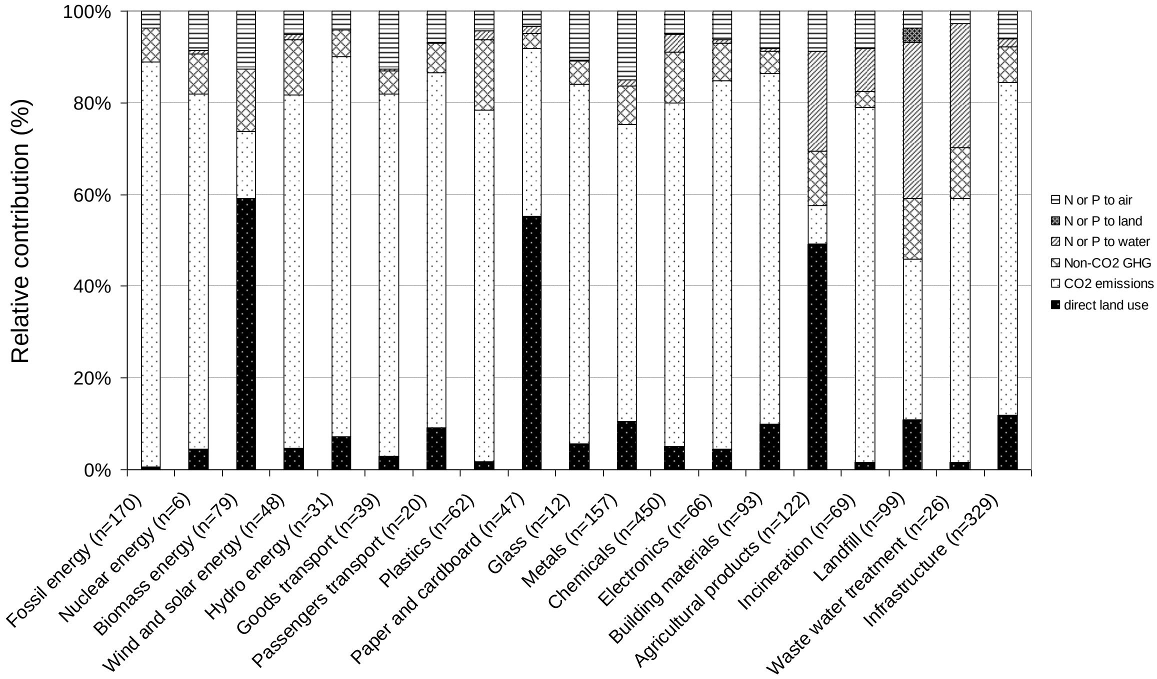
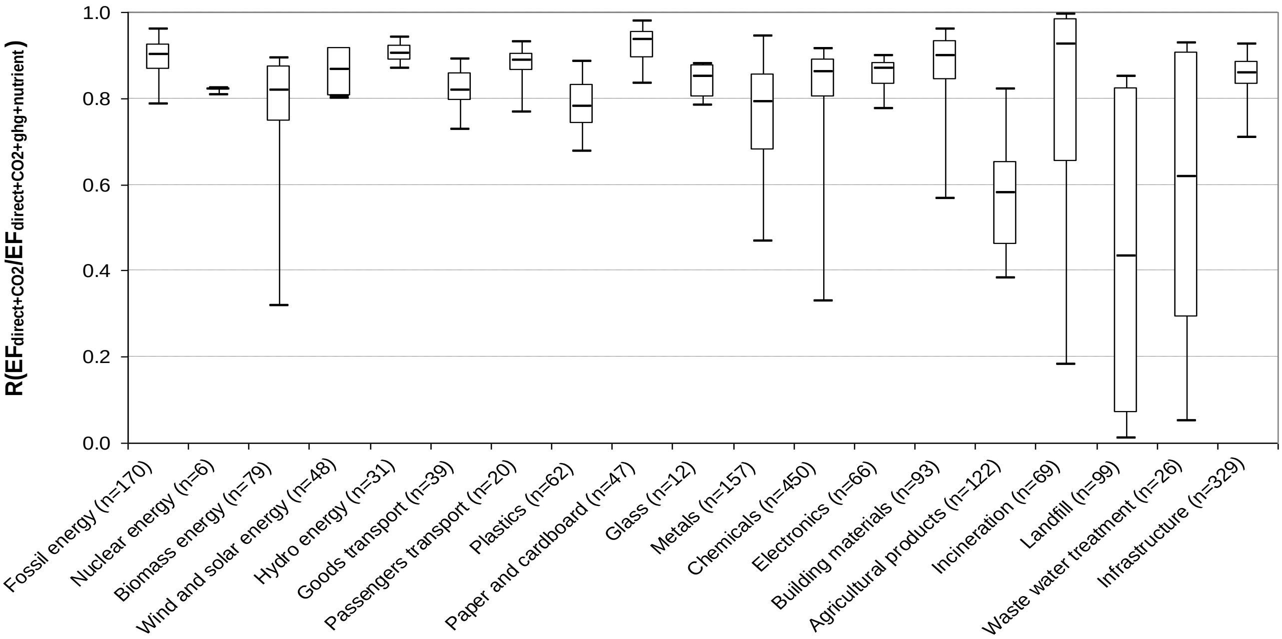


Figure 2. Box plots of the ratios of the original EF and the modified EF scores ($R_{pollutant}$). The centre of the box represents the median value, the edges of the box indicate the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions.



4. Discussion

4.1. Non-CO_2 Greenhouse Gas Emissions

The importance of including emissions of other greenhouse gases into the standardized EF methodology has already been raised in Kitzes *et al.* [30]. Adding non-CO_2 greenhouse gases emissions into the EF calculation in this study evidently resulted in a more complete picture of the environmental burden. CO_2 emissions undoubtedly remain the most important contributors to the EF for most goods and services due to high fossil fuel consumption and a large contribution of direct land use for agricultural products, biomass energy, and paper and cardboards because of extensive land used for crops and forest plantations as a source of wood. However, our results revealed that non-CO_2 greenhouse gases can also substantially contribute to product EFs. Examples are methane (CH_4) emitted from landfill sites, nitrous oxide (N_2O) emissions due to the application of fertilizer in the production of agricultural products, and chlorofluorocarbons (CFCs) emitted during the production of plastics. We used the direct global warming potentials (GWPs) with a time horizon of 100 years, as reported by the IPCC [34], to add non-CO_2 greenhouse gases to our calculations. The 100-year time horizon is the most commonly used in the IPCC [39] and the Kyoto Protocol [40]. The GWP model is the most up to date and scientifically robust model available, based on direct radiative forcing and residence time of the substance emitted.

It can, however, be argued that the GWPs do not reflect the actual bioproductive pathways of synthetic greenhouse gases. The inclusion of the synthetic greenhouse gases, such as CFCs, HFCs, PFCs and SF6, *via* their GWP can be considered artificial, because it is unrelated to the regenerative capacity of the biosphere for these greenhouse gases [30]. In fact, we implicitly assume that extra CO_2 absorption by the biosphere counterbalance the emissions of these synthetic greenhouse gas emissions. Furthermore, the inclusion of the GWP method is considered too complex for some air emissions with an indirect effect on global warming, such as NO_x, SO_2 and non-methane volatile organic compounds (NMVOCs). No GWP values are recommended by the IPCC [36] for these gases that are short-lived and vary regionally in the atmosphere [35]. They are chemically active and even promote cooling effect.

Finally, apart from the 100-year time horizon, the IPCC [34] also reports GWPs for a time horizon of 20 years and 500 years. The choice for a longer or shorter time horizon can change our results. For instance, compared to the GWP in the 100-year time horizon, the GWP of CH_4 is a factor of 3 higher for a time horizon of 20 years and a factor of 3 lower for a time horizon of 500 years. The GWP of N_2O hardly changes for a time horizon of 20 years, but is a factor of 2 lower for a time horizon of 500 years. This implies that for a time horizon of 20 years, CH_4 emissions become more prominent in the EF calculations. For a 500-year time horizon, however, the CH_4 and N_2O emissions become less influential compared to CO_2.

4.2. Nutrient Emissions

Nutrient emissions to all emission compartments, as reported in Ecoinvent, were included in the analysis. Nutrient emissions to water were found to be relevant for the footprint of a number of production processes, particularly within the groups of agricultural products, landfill and waste water treatment. The high amounts of fertilizers used in agricultural practices explain the relatively high N and P emissions to water for this product category. Effluents of waste water treatment plants and leachates from landfill are also known important emission sources of N and P. The EF for nutrients is, however, not without uncertainty. First of all, in the new EF calculations, it is assumed that agricultural soil is the reference compartment to counterbalance N and P emissions, while another reference, such as floodplain soil, may also be used for that purpose [13]. This assumption can seriously influence the removal rates of N and P. Folke *et al.* [13] applied removal rates of P in agricultural systems and N in floodplains of 3–4 and 4–11 kg ha^{-1} yr^{-1}, respectively. The typical removal rates of P and N in our study were, however, set representative for agricultural systems. Particularly for N, we included higher removal rates compared to Folke *et al.* [13]. Higher removal rates result in lower footprints per unit emission (see Equations 6 and 7). Using the removal rates of nutrients reported by Folke *et al.* [13] would therefore result in higher product footprints for nutrient emissions compared to our calculations. Furthermore, the nutrient removal rates can vary within a specific soil system. For instance, the typical denitrification rate of nitrogen in agricultural soils is 65 kg ha^{-1} yr^{-1} but it can be a factor of 4 higher or lower, depending on soil drainage, N application rate and crop type considered. A relatively low denitrification rates can be found in well-drained, aerobic soil conditions with low N application rates and upland crop systems [37]. The uncertainty associated with the nutrient footprints can be reduced by using the actual site-specific nutrient assimilative capacity of the system considered. In the original EF method, land area stands for specific mutually exclusive function. However, the bioproductive land does not function as a resource only, but also provides a system for waste and pollutant assimilation. The issue of double counting may arise if different types of nutrient emissions are summed together. To address this concern, only the most significant or critical emission that needs the largest land has been taken into account. In this analysis, additional agricultural land is being used as a sink for eutrophying substances.

4.3. Comparison to Previous Studies

In the last decade, several modifications have been proposed to improve the original method for calculating EFs [41]. Walsh *et al.* [21] studied the incorporation of methane into the EF analysis in Ireland. They found that the inclusion of methane *via* the GWP increased Ireland's per capita footprint by 20%. We found that the average contribution of non-CO_2 greenhouse gases was up to 16% of the total EF in our study, which indicates a lower importance of non-CO_2 greenhouse gases in product studies compared to the EF calculation of Ireland due to its high methane emissions coming from the agricultural sector. Folke *et al.* [13] calculated the EF of 29 cities within Baltic Europe. They showed that N and P emissions contribute 6.5–8.9% to the total footprint of cities. These numbers correspond well to the typical contribution of nutrient emissions to the overall footprint of goods and services. In a study that included non-renewable resource consumption as an additional category, Nguyen and Yamamoto [42] evaluated the scarcity of non-renewable resources using a thermodynamic approach. They found that the average value of the modified EF was 60% higher compared to the original EF due to the high consumption of mineral commodities such as gold, silver and copper.

5. Conclusions

In conclusion, adding more stressors inherently provides a more complete picture of the EF. We did so for nutrient emissions and non-CO_2 greenhouse gases, maintaining the bioproductivity line of reasoning of the current EF method and preventing double-counting between nutrient emissions. On the other hand, a disadvantage of adding more data is that this information can be uncertain and that the calculation procedure becomes more complex. Concerning the stressors we added to the EF, we show that for most of the products included in our study, the influence of the addition of emissions of nutrients and non-CO_2 greenhouse gases was typically smaller than 20%. The EF was generally dominated by CO_2 emissions or direct land use. However, for goods and services within specific product categories, *i.e.*, waste treatment processes, bio-based energy, agricultural products and chemicals, adding non-CO_2 greenhouse gas emissions to air and nutrient emissions to water can have a dominant influence on the EF. We recommend carefully considering the inclusion of non-CO_2 greenhouse gases and nutrient emissions in EF analyses in which these product categories can play an important role. Our findings suggest that in specific cases, the inclusion of non-CO_2 greenhouse gases and nutrient emissions can indeed change the interpretation of the EF results.

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Appendix A

Table A1. Equivalence factors (EqF) implemented in Ecoinvent for the land use type [7,31].

Ecoinvent classification	EqF for direct land use type (dimensionless)
Occupation, arable	2.2
Occupation, arable, non-irrigated	2.2
Occupation, construction site	2.2
Occupation, dump site	2.2
Occupation, dump site, benthos	0.4
Occupation, forest	1.4
Occupation, forest, intensive	1.4
Occupation, forest, intensive, normal	1.4
Occupation, industrial area	2.2
Occupation, industrial area, benthos	0.4
Occupation, industrial area, built up	2.2
Occupation, industrial area, vegetation	2.2
Occupation, mineral extraction site	2.2
Occupation, pasture and meadow	0.5
Occupation, pasture and meadow, extensive	0.5
Occupation, pasture and meadow, intensive	0.5
Occupation, permanent crop	2.2
Occupation, permanent crop, fruit	2.2
Occupation, permanent crop, fruit, intensive	2.2
Occupation, shrub land, sclerophyllous	1.4
Occupation, traffic area, rail embankment	2.2
Occupation, traffic area, rail network	2.2
Occupation, traffic area, road embankment	2.2
Occupation, traffic area, road network	2.2
Occupation, urban, discontinuously built	2.2
Occupation, water bodies, artificial	1
Occupation, water courses, artificial	1

Appendix B

Table A2. Global warming potentials [34] for a time horizon of 100-years, except for (*) derived from IPCC [35].

Greenhouse gases	GWP 100a (kg CO_2-equivalents kg^{-1})
carbon dioxide	1
carbon monoxide, fossil	1.6*
chloroform	30*
dinitrogen monoxide	298
ethane, pentafluoro-, HFC-125	3,500
ethane, hexafluoro-, HFC 116	12,200
ethane, chloropentafluoro-, CFC-115	7,370

Table A2. *Cont.*

Greenhouse gases	GWP 100a (kg CO_2-equivalents kg^{-1})
ethane, 2-chloro-1,1,1,2-tetra-fluoro-, HCFC-124	609
ethane, 2,2-dichloro-1,1,1-tri-fluoro-, HCFC-123	77
ethane, 1-chloro-1,1-difluoro-, HCFC-142b	2,310
ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	10,000
ethane, 1,1-difluoro-, HFC-152a	124
ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	725
ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	6,130
ethane, 1,1,1-trifluoro-, HFC-143a	4,470
ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1,430
methane	25
methane, bromo-, Halon 1001	5
methane, bromochlorodifluoro-, Halon 1211	1,890
methane, bromotrifluoro-, Halon 1301	7,140
methane, chlorodifluoro-, HCFC-22	1,810
methane, chlorotrifluoro-, CFC-13	14,400
methane, dichloro-, HCC-30	8.7
methane, dichlorodifluoro-, CFC-12	10,900
methane, dichlorofluoro-, HCFC-21	210*
methane, difluoro-, HFC-32	675
methane, monochloro-, R-40	13
methane, tetrachloro-, R-10	1,400
methane, tetrafluoro-, R-14	7,390
methane, trichlorofluoro-, CFC-11	4,600
methane, trifluoro-, HFC-23	14,800
sulfur hexafluoride	22,800

Appendix C

Table A3. Molar mass conversion factor for nutrient emissions to water, soil and air compartments included in our study.

Compartment	Compound	Molar mass of compound (g/mol)	Molar mass conversion factor
Water	N (nitrogen)	14	1
(freshwater, ocean,	NO^{3-} (nitrate)	62	14/62
groundwater and	NO^{2-} (nitrite)	46	14/46
unspecified)	P (phosphorus)	31	1
	PO_4^{3-} (phosphate)	95	31/95
Soil	N (nitrogen)-industrial	14	1
	P (phosphorus)-industrial	31	1

Table A3. *Cont.*

Compartment	Compound	Molar mass of compound (g/mol)	Molar mass conversion factor
Air (high population density, low population density, lower stratosphere and unspecified)	NO^{3-} (nitrate)	62	14/62
	NO_2 (nitrogen oxides)	44	14/44
	NH_3 (ammonia)	17	14/17
	P (phosphorus)	31	1

Appendix D

Figure A1 shows per product group the relative contribution to the EF of direct land use, CO_2, non-CO_2 greenhouse gases and nutrient emissions to water, land and air, using the summed EF instead of the maximum EF for nutrient emissions. The same as for the maximum EF calculation for nutrient emissions, the EF of all product groups is dominated by CO_2 emissions and direct land use. N and P emissions to water contribute on average less than 11%, except for the EF of agricultural products, waste water treatment and landfill, with an average contribution of higher than 20%. N and P emissions to land contribute on average less than 5% for all product categories involved. N or P emissions to air typically add 3–15% to the total EF. The largest difference between summed and maximum EF for nutrient emissions can be found for the agricultural products. For the summed EF, the average share of N and P emissions to water doubles from around 10% to 20% compared to maximum EF.

Figure A1. Relative contribution of direct land use, CO_2 emissions, non-CO_2 greenhouse gases, N and P emissions to water (include nitrate, nitrite, phosphate), N and P emissions land, and N or P emissions to air (include ammonia, nitrogen oxides, nitrate and phosphorus) to the summed EF for 19 product groups.

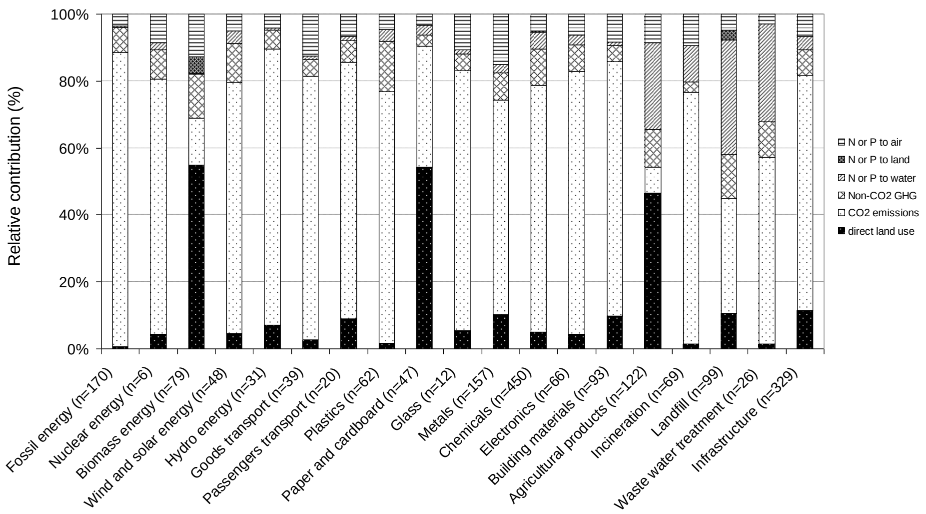

Figure A2 presents box plots of the EF-ratio per product group taking into account pollutants only. The spread reflects the fact that not every product has the same EF-ratio. For most products, the median ratio is larger than 0.75, implying that the added pollutants typically contribute less than 25% to the EF scores. This is, however, not the case for biomass energy, agricultural products, landfill and waste water treatment. For these three product groups, the typical contribution of non-CO_2 greenhouse gases and nutrient emissions is larger, *i.e.*, between 39% and 86%. Specific for the biomass energy, agricultural products and waste treatment categories (incineration, landfill and waste water), it was found that 5% of the processes have an R smaller than 0.2. This implies that for 5% of the waste treatment processes included, the pollutant EF scores are more than 80% determined by nutrients and non-CO_2 greenhouse gas emissions. Compared to the total EF ratios (Figure 2), the extra emissions have a larger influence on the pollutant EF ratios, particularly for the biomass energy and agricultural products.

Figure A2. Box plots of the ratios of the EF for "CO_2 emissions" and "CO_2, greenhouse gases and nutrients emissions". The centre of the box represents the median value, the edges of the box indicates the 25th and 75th percentiles and the whiskers represent the 5th and 95th percentiles of the distributions.