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Review

A Review of the Ecological Footprint Indicator—Perceptions and Methods

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Abstract: We present a comprehensive review of perceptions and methods around the Ecological Footprint (EF), based on a survey of more than 50 international EF stakeholders and a review of more than 150 original papers on EF methods and applications over the last decade. The key points identified in the survey are that the EF (a) is seen as a strong communication tool, (b) has a limited role within a policy context, (c) is limited in scope, (d) should be closer aligned to the UN System of Environmental and Economic Accounting and (e) is most useful as part of a basket of indicators. Key issues from the review of methods are: (a) none of the major methods identified can address all relevant issues and questions at once, (b) basing bioproductivity calculations on Net Primary Production (NPP) is a promising approach, (c) advances in linking bioproductivity with ecosystem services and biodiversity have been made by the Dynamic EF concept and the HANPP indicator, (d) environmentally extended input-output analysis (IOA) provides a number of advantages for improving EF calculations and (e) further variations such as the emergy-based concept or the inclusion of further pollutants are not regarded as providing a fundamental shift to the usefulness of EF for policy making. We also discuss the implications of our findings for the use of the EF as a headline indicator for sustainability decision-making.

Keywords: ecological footprint; perception; methodology; policy relevance

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1. Introduction

The Ecological Footprint (EF) is an indicator that accounts for human demand on global biological resources. It compares the level of consumption with the available amount of bioproductive land and sea area and has been designed to show a possible exceedance of this "sustainability threshold". Originally developed as an indicator of the environmental impacts of nations, individuals or human populations, the EF is increasingly being tried as an indicator of organizational and corporate environmental performance, or even as an indicator of the "sustainability" of products.

There are doubts about this extension of use and the general relevance for policy-making (the most recent discussions, with mixed conclusions, are in [1] and [2]; see also [3] and [4]). What's more, it is clear that there are a number of EF approaches now available, differing in the underlying methodology and the extent to which they address relevant issues that have not been or cannot be dealt with by the standard method described by the Global Footprint Network (GFN).

In this paper we present the results of an expert survey on the perception of the usefulness of the Ecological Footprint as an indicator for sustainability. This is accompanied by a review of all pertinent EF approaches to date and their assessment in the light of the findings from the survey. The objective was to identify and assess existing methods for calculating the Ecological Footprint in terms of robustness and usefulness for (political) decision-making. On the basis of this assessment we draw conclusions as to which methods should be used, developed or combined to yield highest policy relevance.

Both the survey and review address fundamental and critical questions, for example: What exactly do the various Ecological Footprint methods measure? Which environmental/ecological impacts do they include or exclude? How relevant and how robust is the Ecological Footprint for policies and what is desirable from a policy-making point of view?

In the following Section 2.1 we present the key results from the expert survey. The full list of questions and more details on the answers is provided in Appendix A1. In Section 2.2 we present the main results from the literature review of EF methodologies; again, full details are provided in Appendix A2. In Section 3 we discuss the findings and we draw conclusions in Section 4.

2. Results

2.1. Key Results from the Expert Survey

A questionnaire with 20 questions was sent out to 55 internationally recognized experts involved in the use and/or development of the Ecological Footprint. 34 replies were received, equivalent to a response rate of 62%.

The particular aim of the survey was to identify the common understanding and perception of the Ecological Footprint as well as the need for addressing particular issues that are perceived as policy-relevant or otherwise important. We identify five key responses from the survey (for details on questions and answers the reader is referred to Appendix A1):

(1) The Ecological Footprint is a strong communication tool and has a limited role within a policy context beyond this. This was the overwhelming opinion of the experts. This does not mean that the majority of experts did not see value in calculating the Ecological Footprint but would limit its use to

the accounting and communication of over-consumption. Representative expert quote: "*Given its (large number of) deficits and limitations, the EF can only provide a guidance/orientation. Whether it is 25 or 40% [of overshoot] is not the question, the important point is that the EF can illustrate this fact, in particular also to non-experts*".

(2) The EF indicator is limited in its scope. As an aggregated indicator of resource and land use, it provides no information on when ecological limits might be reached related to key ecological services. Representative expert quote: "*I don't think we have enough grips on what are the hard and fast limits yet. And the EF aggregates a range of different impacts under one limit. Whether that one limit makes sense for each of those impacts is open to debate*".

(3) One aggregated indicator is seen as essential for communication but not for providing the level of detail required to undertake a meaningful assessment of regenerative capacity compared with demand. Representative expert quote: "*I think [the EF] needs to include [both] aggregate and components, as the static aggregate figure may remain roughly the same through time but the contributing components may change greatly*".

(4) It would be advantageous to align the Ecological Footprint with the UN System of Environmental and Economic Accounting. Nearly all the experts who have had involvement in the development of the Ecological Footprint and have a history of academic publications of the subject believed this to be very important for its future development. Representative expert quote: "*EF accounting should be compatible [to] the UN System of National Accounts and GDP/GNP indicators, in terms of system boundary and scale, in order to facilitate comparative analysis*".

(5) The Ecological Footprint should be part of a basket of indicators. In isolation, its relevance for (political) decision-making is too limited and therefore a more comprehensive approach is needed. Representative expert quote: "*I think the EF will be a vital indicator which contributes towards this goal as there are limited other indicators which measure and communicate the use and overuse of renewable resources as well as the EF does. […] you would require a number of other complementary indicators to ensure that 'natural resources are able to sustain life' in perpetuity* e.g., *social/economic and environmental*".

2.2. Key Results from the Review of EF Methodologies

Table 1 below lists key issues associated with the Ecological Footprint as identified in the expert survey (rows) as well as the main methodological options for EF calculations (columns). Input-output analysis as an option for the allocation of EF impacts to consumption and trade has also been extensively reviewed (see Appendix A2) but has not been included in Table 1 as it is not an EF method in itself.

Table 1. Characteristics of different Ecological Footprint methods (for details see Appendix A2).

Key Issues	**NFA** (National Footprint Accounts)	**Land disturbance**	**Emergy**	**EF-NPP** (Net Primary Production)	**Dynamic EF**	**Further extensions** (several approaches)
Takes into account:						
Ecological limits	indirectly	accounts directly for biodiversity of vascular plants	indirectly	indirectly	accounts directly for threatened species	
Depicts overshoot	yes	yes	yes	yes	no	
Crop productivity	yes	yes	yes	yes	yes	
Overgrazing	no	indirectly	no	no	indirectly	
Desertification	no	indirectly	no	no	indirectly	
Land erosion	no	indirectly	no	no	indirectly	
Eutrophication	no	no	no	no	no	Acidification by [5]
Deforestation of primary forests	indirectly	indirectly	no	indirectly	indirectly	
Threat to species (reproductive rates)	no	no	no	no	no	
Biodiversity (number of species)	no	partly	no	possible	yes	
Overfishing	indirectly	no	no	indirectly	no	
Impacts of fish farming/aquaculture	no	no	no	no	no	
Ecosystem services	no	partly	no	possible	yes	
Water shortages	no	no	no	no	no	
Ecotoxicity	no	no	no	no	no	Toxicity by [6]
Impacts of non-biological resources	no	no	no	no	no	Included by [7]
Climate change	indirectly	indirectly	no	indirectly	yes	Methane included by some authors
Technical features:						
Endogenous modeling of future impacts	no	no	no	no	yes	
Compatibility with SEEA	low	high	no	low	high	
Unit used (per year)	global ha	disturbed ha	global ha or ha	global ha	ha or t	
State & scope of implementation (availability of method)	high	high	low	high	low	
Availability and reliability of data (e.g., from official data sources)	high	medium	low	high	medium	

Table 1. *Cont.*

Key Issues	**NFA** (National Footprint Accounts)	**Land disturbance**	**Emergy**	**EF-NPP** (Net Primary Production)	**Dynamic EF**	**Further extensions** (several approaches)
Specific applications:						
Identifies the risks and opportunities for a country in a resource-constrained world	yes	yes	yes	yes	yes	
Identifies what natural assets a country has and whether these are in decline	partly (via biocapacity)	partly (via biocapacity)	no	partly (via biocapacity)	partly (via biocapacity)	
Identifies whether technological changes have helped to compensate for increases in resource demand	no	no	no	no	yes	
Key references:	[8]	[9]	[10,11]	[12]	[13]	

In the following we list the main findings from the literature review; full details are provided in Appendix A2.

(1) None of the methods listed above can address all relevant issues and questions at once. Methods trying to establish a quantifiable link between human consumption, ecosystem functioning and bioproductivity are emerging. This link is arguably strongest in the dynamic Ecological Footprint (DEF) model where biodiversity is explicitly addressed and future scenarios can be enumerated, similar to the approach in IPCC models. DEF is, however, also the method that is most different from the conventional approach, does not indicate overshoot and has only been described in a research report so far.

(2) Basing bioproductivity calculations on Net Primary Production (NPP) is a promising approach that provides an explicit link between human consumption and ecosystem services. EF-NPP relates overuse of land related to land productivity, whereas the overshoot measured by the EF alone in essence results from a translation of carbon dioxide emissions into virtual land. Although the current EF-NPP approach stops short of defining the sustainable use of NPP, further research is investigating this possibility. Some studies have, for example, investigated and established the link between NPP and biodiversity, the further exploration of which would have a high potential for the EF-NPP method. The land disturbance approach also takes into account impacts on plants.

(3) Further variations such as the emergy-based concept or the inclusion of other impacts or pollutants are not regarded as providing a fundamental shift to the usefulness of EF for policy making. They might, however, help to address specific research questions and assist in ironing out some of the inconsistencies of the conventional approach. A combination with other methods might therefore be an option in specific cases.

(4) The main advantage of input-output analysis lies in its unambiguous and consistent (SEEA-compatible) accounting of all upstream life-cycle impacts and the good availability of

expenditure data that allow a fine spatial, temporal and socio-economic breakdown of consumption Footprints. Employing IOA does not actually create a new EF method as such.

(5) For the correct allocation of Footprints embodied in international trade, bespoke multi-region input-output (MRIO) models are identified as the ideal method. Once fully developed, MRIO will be particularly suitable in the future to estimate the Ecological Footprints of imports and exports of nations with the possibility to track their origin via inter-industry linkages, international supply chains and multi-national trade flows. However, this will require further development.

3. Discussion

The main strengths of the Ecological Footprint—as confirmed by the expert survey—are (a) its ability to condense the size of human pressure on different types of bioproductivity into one single number, (b) the possibility to provide some sense of over-consumption, and (c) the opportunity to communicate results to a wide audience. The key question though is whether the Ecological Footprint allows for a more specific assessment beyond these broad-brush indications. Do these advantages still hold if the EF is broken down into its individual components or if it is applied at the micro level of production and consumption, e.g., for individual products? Or are other indicators better suited at this level?

With respect to energy and carbon a separate indicator, the 'carbon footprint', has been established. Consumption-based accounting of greenhouse gas emissions has been carried out for decades as part of life cycle assessment (LCA) in the impact category global warming potential (GWP) [14]. The idiom 'carbon footprint' however, has only developed over the last few years [15]. Both, the use of the term carbon footprint in the public domain as well as applications in the public and private sector have now overtaken the Ecological Footprint by far. Three significant standardization processes (for an overview see [14]) as well as a number of research reports and journal papers (e.g., [16-20]) have boosted the carbon footprint's popularity despite ongoing discussions about its exact definition and appropriate calculation methods ([15,21-24]). All these carbon footprint calculations use tons of CO_2 equivalents as a unit (some studies include other greenhouse gases than CO_2) and address specifically just one category of environmental pressure: amount and source of emissions that lead to global warming. Whilst Kitzes *et al.* [4] argue that there are advantages in translating tons of carbon dioxide emissions into global hectares as this would allow a comparison with other demands on productive land, Wiedmann and Minx [15] make the point that the underlying assumptions of this conversion would increase the uncertainties of carbon footprint calculations.

A similar situation arises with the "water footprint" (WF) which was introduced in 2002 by A.Y. Hoekstra from the University of Twente and has developed as a separate indicator altogether, measuring human appropriation of freshwater resources (see e.g., [25-27]). In contrast to the EF which accounts for biologically productive marine areas as well as water areas used for hydropower, the WF accounts for the total volume of freshwater that is used to produce the goods and services consumed by an individual or community. Similar to the other members of the 'footprint family' it aims to capture the virtual (embodied) use of water along the production life cycle and allocates the total to consumption.

Conceptually similar to the virtual water approach is the notion of embodied HANPP (eHANPP) which links net primary production in one region with a particular level of biomass consumption in another region by taking into account trade in biomass [28,29]. Mapping the spatial disconnect between net-producing and net-consuming regions can provide additional insights on the impacts of biomass production and consumption chains on ecosystems. Both WF and eHANPP answer different research questions than the EF and can be seen as complementary indicators (see also [30], p. 11).

With respect to commodities such as crops, meat, fish and wood, the conventional EF method is confronted with the failure to distinguish between sustainable and unsustainable yields [31-33]. This, however, is crucial if ecological sustainability is the focus of attention going beyond mere bioproductivity accounting. Measuring the sustainability of yields requires bespoke methods for each individual bio-product (e.g., detailed research into fish populations and safe catching quotes *etc.*; for details see Appendix A2, Section A). One single indicator will not be able to cover this wide field.

One crucial feature of the EF is that the main cause of "overshoot" is the use of fossil fuels. Data from the Global Footprint Network (GFN) has been given in Table 2 to illustrate this point. The data provide the total global Ecological Footprint against total available biocapacity for 2005.

Table 2. World total Ecological Footprint and Biocapacity 2005 in gha/cap [34].

	Carbon	**Crop-land**	**Grazing land**	**Forest**	**Fishing ground**	**Built-up land**	**Total**
World Total Ecological Footprint 2005	1.41	0.64	0.26	0.23	0.09	0.07	**2.7**
World Total Biocapacity 2005		0.64	0.37	0.81	0.17	0.07	**2.1**
Ecological deficit							**–0.6**

The method employed by GFN implicitly assumes that no land has been specially set aside for carbon storage. For cropland available space is equal to global biocapacity. As cropland generally provides its output annually this will always be the case. It is impossible to use more cropland than was allocated as cropland. The situation is different for grazing land, forest and fishing ground where stocks exist. In these cases, none of them exceed biocapacity on a global level. Therefore, total ecological deficit (or ecological overshoot) is solely due to carbon. At the global level the Ecological Footprint is telling us nothing more than human activity is responsible for excessive carbon build up in the atmosphere.

In addition to this, the EF also has the potential to underplay the carbon issue as available biocapacity from grazing land, forest and fishing ground are all in credit. Without these land types, the ecological overshoot from carbon alone would be more than 2.3 times higher.

In conclusion, for 'mere' carbon and water footprint accounting other methods than the EF have been established and successfully employed over the last few years. For commodities, although there is some merit in identifying the different bioproductivity demands of biofuels with the EF [4], more sophisticated methods of ecological research will have to be used to come to comprehensive conclusions (compare to [35]).

Of course, looking at disaggregated, single indicators alone always bears the danger of losing sight of the bigger picture—a point well made by Finkbeiner [14]—which is why aggregated information

such as the total Ecological Footprint will continue to have its value. Even more so, if this is accompanied with areas not covered by the EF, like it is for example done in the Living Planet Report 2008 where the Living Planet Index and the Ecological Footprint are juxtaposed with the water footprint.

Methodologically, further improvements will have to be made to the Ecological Footprint to make it as robust and relevant as other widely accepted indicators. Input-output analysis (IOA) has already widely expanded the application of the Ecological Footprint, particularly in the area of policy formulation related to the distribution of human appropriation of biocapacity. This, for example, helps to address questions related to equity. Furthermore, combining EF with IO analysis has proved to be a useful way to increase the robustness of the EF indicator, further the alignment with the UN-SEEA and widen the scope of relevant applications. Multi-region IOA is emerging as an appropriate modeling technique [36,37].

Alignment of Ecological Footprint accounting with the UN-SEEA would help with standardizing the accounting processes and improve the accuracy of allocation. Such a process would be accomplished by aligning the basic components of the EF with SEEA sectors, making them available for further use in IOA and other analyses. However, the underlying, fundamental methodological questions are not addressed by SEEA alignment alone.

Complementary indicators are required to monitor progress related to other environmental issues not covered by the Ecological Footprint. One specific example is the suggestion in [38] for a basket of four indicators to monitor progress on the EU's Resource Strategy: Ecological Footprint (EF), Environmentally-weighted Material Consumption (EMC), Human Appropriation of Net Primary Production (HANPP) and Land and Ecosystem Accounts (LEAC). Additional indicators would be required to capture sustainable yield thresholds, impacts on ecosystems or the geographical distribution of pollution impacts.

Methods have been developed and suggested that str*etc*h beyond bioproductivity accounting and link to ecosystem services, biodiversity and/or pollution. Currently the most advanced approaches in this respect are the dynamic EF concept and the HANPP indicator. The potential for a more *Ecological* Footprint is there but further development is needed.

4. Conclusions

In conclusion of the survey, the experts perceived that it is time to be clearer about the Ecological Footprint and recognize it as a powerful tool for communicating over-consumption of humanity whilst being aware of its limitations in other areas. It can act as a strong statement in reports to identify and communicate potential sources of unsustainability to the general public and to political and corporate decision-makers. This is a clear statement of over-consumption that has still not been accepted by governments or thought about widely by the general public. However, the Ecological Footprint as it stands now cannot provide the information by which to conduct profound policy assessment. In the quest to derive an indicator that can challenge GDP, statements have been made about the Ecological Footprint that are not always in line with its scientific rigor or application potential.

There are cases (often very subtle) where an impression of the capabilities of EF is given which it cannot quite fulfill. This has the potential to undermine the powerful measure of ecological overshoot.

One example is Figure 4 in the Living Planet Report 2008 showing causes and effects of human pressure [34]. In this context the LPR 2008 states on page 4, 3rd column, that "The Ecological Footprint is an aggregate measure of the demands that resource consumption places on ecosystems and species". While neither the figure nor this statement is actually wrong, both together might lead the (quick) reader to the conclusion that the EF could actually inform (policy-makers) about any of the "Threats or Pressures" named in the last column of Figure 4. The survey undertaken in this study however, showed that this is clearly not the case. Other examples would be statements about the sustainability of products or businesses using the EF as an indicator.

The Ecological Footprint cannot answer the question how long ecological overshoot will be possible, and possible for what. Globally, a two or more degree rise in global atmospheric temperature from human induced climate change has been labeled as "dangerous climate change" by the IPCC. This will have deplorable consequences in terms of human mortality as well as further positive feedback loops, the true extend of which is only beginning to be discovered by scientists. In all the literature, it is this that provides the clearest statement of what happens when we exceed ecological limits. In reality, ecological limits are therefore intrinsically linked to human consequences. Limits are a scientifically subjective concept about the (non-)acceptability of threats to human life.

Should the Ecological Footprint ever be more than a mere tool for communicating over-consumption? After all, Rapport writes [39]: "The survival of humankind […] depends upon far more than only the resource demands placed on the earth.… The challenge to humankind […] lies not only in reducing the size of the ecological footprint, but also in increasing the prevalence of healthy ecosystems. […] maintaining ecosystem health is essential to sustain the ecological goods and services upon which EF accounting is based".

Methodological developments are indeed under way that try to strengthen the link between human consumption and ecological limits, not only in the area of climate change but importantly in the areas of ecosystem health, biodiversity and sustainability of agricultural, land management and fishing practices. They might be able to help addressing the sheer complexity of the issue; a challenge that the Ecological Footprint has not mastered yet.

Whether or not the Ecological Footprint needs to be more "ecological" in its roots is a question that ultimately all users of the indicator need to decide. It is clear that the Ecological Footprint is one of the indicators needed to deliver the message of ecological unsustainability. If anything, the pedagogical language around the Ecological Footprint could be stronger while the scientific claims are moderated.

All the survey respondents had a good working understanding of the Ecological Footprint or knowledge in the field of sustainability indicators. However, from the responses it was clear that there are many misconceptions of the Ecological Footprint even within an expert group, let alone a policy audience who are likely to know even less about the technical details. This is a major concern and greater honesty combined with clearer statements of limitations is required in both the academic literature and policy publications.

Our review clearly recognizes the contribution of the Ecological Footprint but also clearly indicates what it can and cannot tell us. Being clear and honest about this will ensure that the Ecological Footprint has a future.

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Appendix A1. Detailed Questions and Answers from the Expert Survey

In this section we list the survey questions and details of the answers given by the experts. Not all of the experts have detailed knowledge of the methodology which is why some of the answers might technically not be correct or reflect concerns with the Ecological Footprint that have been addressed in the academic literature. However, the aim of the survey was to capture the perception (as well as the actual knowledge) of the EF and therefore a reflection of how the reporting of the EF is received.

A1.1. Scope of Survey and Questionnaire

A questionnaire with 20 questions was sent out to 55 internationally recognized experts involved in the use and/or development of the Ecological Footprint. 34 replies were received, equivalent to a response rate of 62%.

The particular aim of the survey was to identify the common understanding and perception of the Ecological Footprint as well as the need for addressing particular issues that are perceived as policy-relevant or otherwise important. Participants were asked to answer questions with ‘yes’, ‘no’ or ‘don’t know’ and provide additional comments for clarification. The following questions were asked.

A1.2. Questions about the Existing Ecological Footprint Indicator and Methodology

The questions under this category referred to the Ecological Footprint (EF) as defined by Wackernagel & Rees [40] and used by Global Footprint Network and WWF in its Living Planet Reports (e.g., [34]). There, the Ecological Footprint is defined as: “A measure of how much biologically productive land and water an individual, population or activity requires to produce all the

resources it consumes and to absorb the waste it generates using prevailing technology and resource management practices".

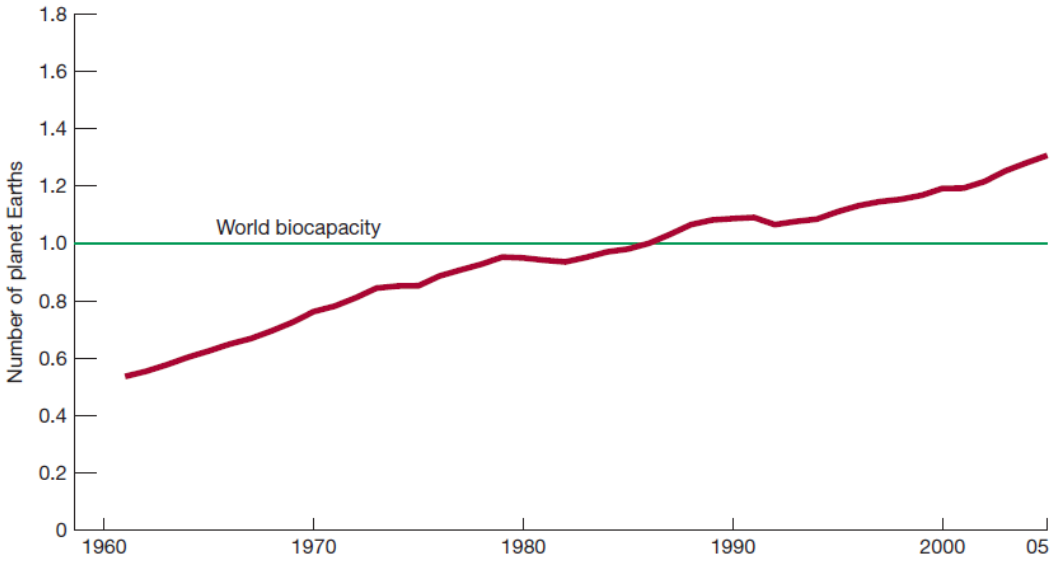
Question 1

Do you think the definition provided above is adequate?

Question 2

According to the graph below, which shows the development of the global Ecological Footprint from 1961 to 2005, humanity was "living within the Earth's ecological limits" until 1986 whereas after 1986 these limits have increasingly been exceeded every year. Do you think this was the case?

Figure 1. Global Ecological Footprint, 1961–2005 [34].



Question 3

The term "(ecological) overshoot" is defined as follows: "Global overshoot occurs when humanity's demand on nature exceeds the biosphere's supply, or regenerative capacity. Such overshoot leads to a depletion of Earth's life supporting natural capital and a build-up of waste". Do you think the EF as defined above is able to measure ecological overshoot?

Question 4

In your opinion, does the Ecological Footprint as defined above provide information about the following issues (see also Question 11)?

- Crop productivity
- Overgrazing
- Desertification
- Land erosion
- Eutrophication
- Deforestation of primary forests
- Threat to species (reproductive rates)
- Biodiversity (number of species)

- Overfishing
- Impacts of fish farming/aquaculture
- Ecosystem services
- Water shortages
- Ecotoxicity (e.g., bioaccumulation of persistent pollutants)
- Impacts of mining of non-biological resources (e.g., open pit mining, precious metal mining, *etc.*)
- Climate change

Question 5

Do you think that there can be one aggregated indicator that measures ecological limits? If yes, please specify.

Question 6

WWF's "Footprint Meta-Goal for 2050" is: "By 2050, humanity's global footprint stays within the earth's capacity to sustain life and the natural resources of our planet are shared equitably". Do you think that the EF as defined above is an adequate indicator to measure progress towards this goal?

Question 7

Is the EF as an aggregated indicator useful for policy making? If yes, please mention below the policy areas in which you think it is relevant/useful. If no, please explain why.

Question 8

Can the Ecological Footprint help answer any of the following?

- Identify the risks and opportunities for a country in a resource-constrained world
- What natural assets a country has and whether these are in decline
- Whether technology advances have helped to compensate for increases in resource demand
- Help citizens live better lives with fewer resources

Question 9

Do you think that the existing EF standards are adequate to establish sufficient robustness for decision-making? If no, please briefly mention below the issues that need addressing in your opinion.

A1.3. Questions about DESIRABLE Aspects of the Ecological Footprint Indicator and Methodology

These questions do not refer to one specific EF methodology but are meant to identify the general need for certain aspects of the EF indicator.

Question 10

Is it desirable to have one aggregated indicator on ecological limits?

Question 11

Is it desirable that the Ecological Footprint is able to take into account any of the following (independent of whether it already includes this aspect or not)? (Same list as under Question 4).

- Crop productivity
- Overgrazing
- Desertification
- Land erosion
- Eutrophication
- Deforestation of primary forests
- Threat to species (reproductive rates)
- Biodiversity (number of species)
- Overfishing
- Impacts of fish farming/aquaculture
- Ecosystem services
- Water shortages
- Ecotoxicity (e.g., bioaccumulation of persistent pollutants)
- Impacts of mining of non-biological resources (e.g., open pit mining, precious metal mining, *etc.*)
- Climate change

Question 12

Is it desirable that future impacts can be estimated by using the Ecological Footprint (similar to climate change scenarios estimating future atmospheric temperatures)?

Question 13

Is it desirable that the Ecological Footprint of an organization can be calculated?

Question 14

Is it desirable that the Ecological Footprint is able to quantify/estimate the impacts associated with the production of a single product along its (international) supply chain (e.g., a cup of coffee from plantation to consumer)?

Question 15

Is it desirable that the Ecological Footprint is compatible/consistent with other established methods of economic and environmental accounting? If yes, which other methods are relevant?

Question 16

Do you think it would be more useful to present the EF not as an aggregated indicator but only its components such as carbon (area) footprint, land footprint, marine areas, *etc.*

Question 17

Do you think the unit ‘global hectares’ should be replaced or complemented by one or several other units (e.g., hectares of land, tons of GHGs, *etc.*)? If yes, please briefly explain why.

Question 18

In your opinion, which initiatives/developments would help to strengthen the ability of the Ecological Footprint indicator to inform policy making?

- Combination of different methodologies
- Alignment of method with UN System of Economic and Environmental Accounts (SEEA) (with the possible goal of inclusion)
- Standardization by International Standards Organization (ISO) or similar organization (which one?)
- Certification of studies/tools
- Open tender for methodological development
- Endorsement by public bodies (e.g., national statistical offices), possibly supported by public funding

Question 19

What would be required in order for the proponents of different EF methods to agree on and jointly communicate best footprint practice in order to strengthen the case for urgent policy measures to reduce human pressure on global ecosystems?

A1.4. Questions about Personal Involvement with the Ecological Footprint

These questions refer to your involvement with the Ecological Footprint.

Question 20

Are you a…
… developer of an EF methodology
… user of EF results
… EF practitioner applying one particular methodology
… policy maker using evidence from EF studies
… member of the Global Footprint Network
None of these. I am …

A1.5. Response to Question 1: Defining the Ecological Footprint

Question 1 asked the experts whether the definition of the Ecological Footprint provided by GFN was an adequate description.

Many of the experts believed that it was a too optimistic in a number of key areas. In particular this related to the claim that "all resources" as well as "all wastes" were covered within the Ecological Footprint. One respondent believing that,

"The EF does not make comments about 'all resources' but a subset of biotic resources".

To some extent this is true, however to calculate the "energy land" component there is an attempt to include more than biotic resources, but not from the perspective of land use. Other experts also suggested that the important resource of water was also excluded.

A similar issue arose with the claim that the Ecological Footprint includes "to absorb the waste it generates". A respondent's reply being,

"Waste is not considered at all and in terms of emissions, only CO_2 is addressed (at least at the moment). The description should be more precise in this regard".

Further respondents picked up on this issue highlighting the point that not all waste streams can be expressed in requirements for biologically productive space.

Further concerns were raised about the term "demands on nature", stating,

"There can be some confusion with the use of the words 'demand on nature'. For me it's more appropriate [to refer to]: demand of renewable resources and services, because the word 'nature' can include also the extractions of minerals *etc*, that EF cannot account [for]".

In reality, a definition of the rather abstract concept of the Ecological Footprint will always be difficult, but should attempt to be as clear as possible ensuring that claims to cover all resources are adjusted as well as clearer definition of "waste", *i.e.*, excessive carbon dioxide output from fossil fuel sources.

Finally, one expert raised the issue that the goal of the Ecological Footprint was significantly more important and it made more sense to judge this as opposed to a definition. In reality, these are two separate issues. The definition of the Ecological Footprint must be able to adequately define the scope of the indicator as this will be used in every publication of the subject.

A1.6. Response to Question 2: Exceeding Ecological Limits

The experts were presented with the graph showing the global Ecological Footprint from 1961 to 2005 [34] and asked to comment on whether they trusted this information in terms of exceeding limits in 1986.

There was significant doubt that an indicator of any description could provide a complete and robust answer to whether ecological limits have exceeded. The point made by many of the experts highlights that the concept of ecological limits is subject to definition and our knowledge of them. In response to the question, many respondents suggested that they would have no way of knowing that ecological limits have been exceeded with information from one indicator. Doubt was also raised as to whether the Ecological Footprint was robust enough to make that claim.

There are numerous examples where attempts have been made to assess ecological limits. These have predominately failed. This leads to the point that ecological limits by definition are an anthropocentric concept. Nature in itself has no knowledge of limits.

This issue is clearly seen when looking at the issue of climate change. Historically, it is possible to identify much higher global temperatures than what is currently being experienced due to human induced climate change. However, the fact that no human was living during this time means that no (ecological) limits existed. Today, IPCC scientists suggest that a global temperature rise above two degrees by 2050 will lead to catastrophic consequences. Therefore, many of the experts highlighted the importance of understanding the difference between "ecological limits" and "ecological overshoot". However, there is significant evidence that this distinction is blurred in the literature.

Some respondents who had engaged with the Ecological Footprint made commitments that related to the fact that this information was probably an underestimate of the real situation. One respondent stating,

"It is a conservative measurement and, as defined, likely to have occurred before the mid 80s".

Again, this refers to ecological overshoot as opposed to limits. Many respondents believed that ecological limits were exceeded before 1986, demonstrating that they don't think the Ecological Footprint is an adequate measure to 'pinpoint' overshoot.

This was followed up by the comment that for communication purposes this is acceptable; it provided a powerful measure of an important issue. This point was made by many of the respondents, one suggesting,

"Given its (large number of) deficits and limitations, the EF can only provide a guidance/orientation. Whether it is 25 or 40% is not the question, the important point is that the EF can illustrate this fact, in particular also to non-experts. The message is therefore to raise awareness rather than to question, if overshoot began in 1986 or 1996".

It was also highlighted that the year when ecological overshoot occurred will change as methodologies are updated. This is a generic problem with any indicator. Adjustments are made constantly to all indicators and the fixation on a specific date does cause problems. It is not possible to expect no change in results.

In many respects, this raises the issue as to what can be expected from the Ecological Footprint. If we are looking for an indicator to add to the growing body of evidence that human activity has ensured that some ecosystem services [41] are being exceeded, then the Ecological Footprint achieves this, according to many of the experts. Indicators related to carbon dioxide emissions and their associated increase in atmospheric concentrations also raises this issue, as well as research into fishing stocks and the capacity of forests to regenerate themselves.

However, does the Ecological Footprint draw all these issues together to provide a complete global assessment of ecological limits? This is where many respondents were doubtful. Two relevant comments being,

"It seems that the degradation of natural capital such as land productivity is not revealed with such an analysis".

"I think this graph has only pedagogic value—placing urgency into arguments concerned with the finiteness of the Earth. To say that the Earth was living within, or overshooting, its 'ecological limits' from an indicator which measures purely biologically productive land and water is in my opinion misleading. Other sustainability measures show other trends".

No one doubted that this is an important issue that needs attention by the policy audience and the general public and the benefits of the Ecological Footprint to communicate ecological overshoot was clear. However, is the EF an indicator that could be used to state whether humanity is living within ecological limits? The answers to this reflected a clear no. Not one respondent either suggested that they felt this assessment was robust enough to give an accurate picture of the global situation.

To distance the Ecological Footprint from the terminology of ecological limits, one respondent suggested that,

"It could be more appropriate to say that before 1980 humanity was using an amount of renewable resources and services *regenerable* by the planet ecosystems in less than one year".

This is clearly different from ecological limits and is a more precise description of the information available, as provided by the Ecological Footprint.

A1.7. Response to Question 3: Ecological Overshoot

The key issue for many of the respondents was what the Ecological Footprint was telling us about ecological overshoot. For many experts, there was the belief that it was an expression of excessive carbon built-up in the atmosphere, as highlighted by the three comments below.

"In the EF, overshoot can only happen through unsequestered GHG emissions. Hence, the measure of overshoot is critically dependent on the assumptions behind converting emissions into area. However, having said this, overshoot is a nice communication vehicle".

"The EF can illustrate overshoot with regard to one key category of resource use: energy/CO_2 emissions. The EF is surely not able to illustrate overshoot in other key areas. I would also argue, not even regarding land use, as the use of global hectares abstracts from real land use".

"The main cause of the overshoot, as measured by the EF, is the fossil fuel dependency".

Other comments by the experts expressed this concern stating,

"It is simply too 'coarse' of an indicator to achieve this. Its sole focus on biologically productive land and water is very limited in this regard. There are many scarce resources in addition to biologically productive land and water".

"I would not say that it is able to 'measure' overshoot. I guess I rather believe it is useful to communicate overshoot in an aggregate way. This is useful to some extent, but should not be overstretched".

The EF indicator is a measure of flows as opposed to overall changes in stocks. It is possible for the Ecological Footprint to demonstrate that the yearly balance for biocapacity has gone down but it is not a precise measure of biological stocks. In this respect, it is a flow indicator of biocapacity measured in units of stocks.

In conclusion, for the aim to express human pressure on nature, the Ecological Footprint is too limited and too coarse.

A1.8. Response to Questions 4 and 11: Ability to Inform Key Environmental Concerns

As a follow on from the last question, the experts were asked to express whether the Ecological Footprint had further application beyond the issue of ecological overshoot and environmental limits.

All the environmental concerns were taken from the publications produced by GFN given to governments to engage them with the Ecological Footprint. The documents highlight that the Ecological Footprint had something useful to say about all the issues. This was not an opinion that was shared by surveyed experts, as illustrated in the figure below.

The only issue where the majority of experts perceived that the Ecological Footprint had value, related to crop productivity. 45% suggested that the Ecological Footprint had relevance to climate change and ecosystem services. Apart from these issues, the majority of other responses reflected that the Ecological Footprint had limited or little relevance to these issues.

When asked what the Ecological Footprint should inform the survey experts expressed the opinion that they would like to see all the issues covered, expressing the desire that one aggregated indicator that could encompass a large number of environmental concerns would be beneficial.

Figure 2. Response rates to the question "Does the Ecological Footprint provide valuable information on the following issues?"

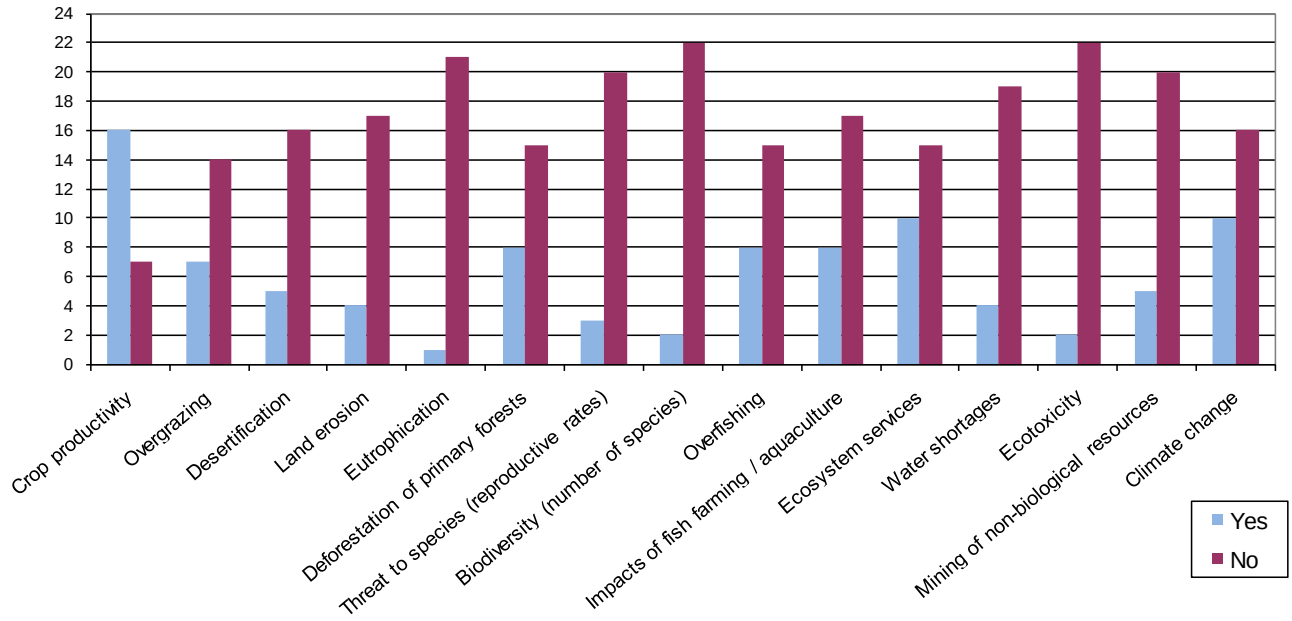
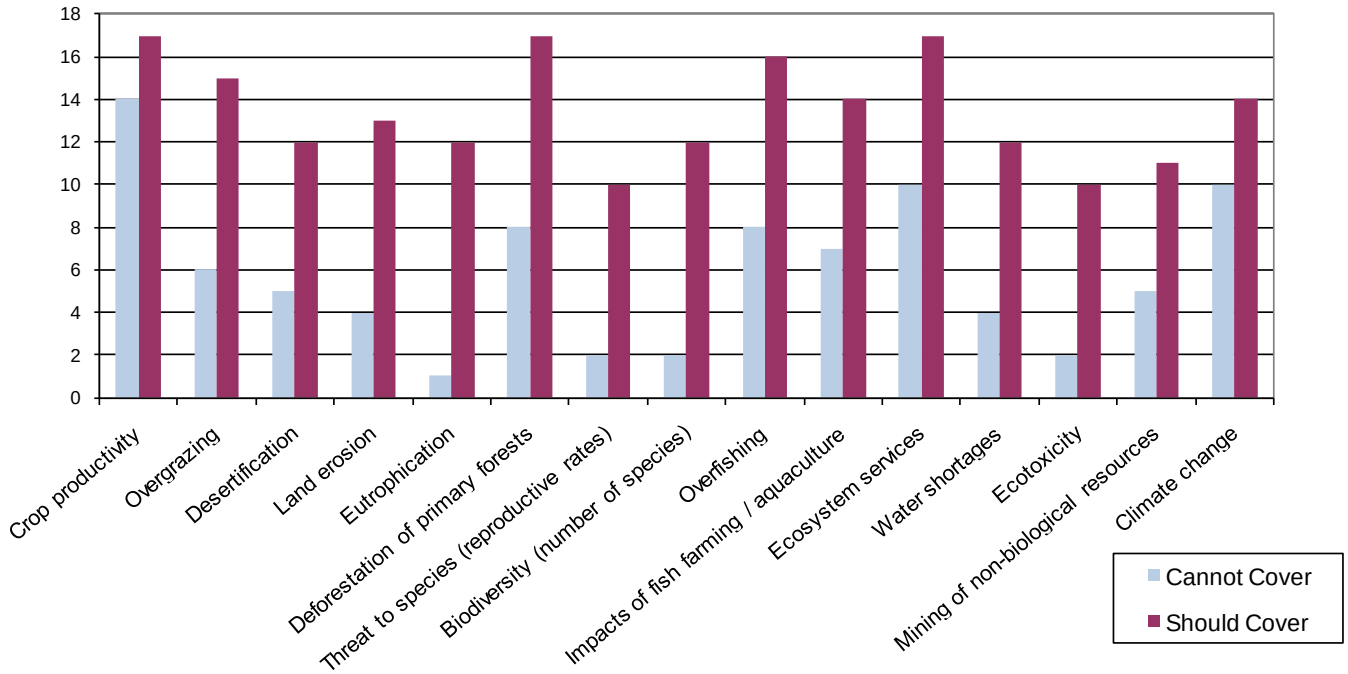


Figure 3. Response rates to the question "Is it desirable that the Ecological Footprint is able to take into account any of the following (independent of whether it already includes this aspect or not)?"



One survey expert did highlight that the Ecological Footprint does not attempt to answer these questions and that therefore it would be unfair to assess the indicator against this criteria, stating,

"As stated by GFN the EF only makes comment about what is, however temporal analysis can be indicative of trends in factors such as desertification, crop productivity *etc.* Care should be given to

ensure that the EF is not used in a way that it was not meant to be. Many EF criticisms in the literature result because of this".

"It covers I think correctly what it was designed to cover, and I think we're at a threshold where any further expansion threatens to dilute the results".

Many of the survey experts returned to the issue about the application of the Ecological Footprint, believing that its value lies to communicating a key overall measure of over-consumption and that it is not designed to cover such issues.

"I consider the EF to be a powerful consumptive tool (measuring impacts of consumption) rather than having any real meaning on measuring impacts and limits of production".

"I have mostly used the EF as an OVERALL and GENERAL indicator (or to be more precise; index), thus not used it for 'issue-specific' information".

Other comments related to the fact that the Ecological Footprint is a statement of potential "increased pressure on the environment" and nothing more.

"But does not give direct evidence of why things are as they are. There are at best indirect indications, e.g., an increase in the EF is likely to put pressure on species, but again, how their diversity would be affected cannot be concluded from the EF".

Finally, the majority of the experts saw value in the Ecological Footprint running alongside other indicators that had specific meaning to the issue in question.

"Other associate indicators may be used on conjunction with the EF, as seen in the Living Planet Report".

"The EF, by nature, cannot take some of these into account no matter how much the methodologies are worked on and improved. However, the more these issues can be taken into account and incorporated into current methods, or even just communicated somehow alongside EF results, the better".

"But in each category, there are better indicators then the EF. Each issue needs its special tools".

"I think the EF can be used to monitor aggregate resource demand (mostly for public communication), suggesting that we are causing problems in all these fields through excessive resource demand. I would not tackle any of these issues scientifically by using the EF, however. In all of these fields, more useful measures and indicators are available to measure human-induced pressures or detect problems".

There will always be issues with aggregated indicators. Life Cycle Assessment (LCA) has attempted to do this for many years and there has always been considerable criticism about this valuation process.

It is not about the Ecological Footprint providing information on these environmental issues, but more about whether that environmental issue has been taken into account in the Ecological Footprint's assessment of human appropriation of biocapacity. However, is this necessary? It would not change the measure of the Ecological Footprint; that over-consumption means ecological overshoot. The measure is clear and relevant.

In conclusion, if the aim was to provide an assessment of environmental concerns listed above then further indicators are required as the Ecological Footprint would be inadequate on its own.

A1.9. Response to Questions 5, 10, 16 + 17: Aggregated Indicators

Leading on from this question, the experts were asked to give their opinion on aggregated indicators. Nearly 70% of respondents answered that it is not possible for one aggregated indicator to measure ecological limits. There was overwhelming response that aggregated environmental indicators lost meaning due to aggregation, were too imprecise to offer meaningful analysis and could not provide useful information on the complex environment in which we live. A selection of quotes has been given below to demonstrate these concerns.

"Ecology is a multi-facetted and complex discipline, because the environment is complex. We need detailed information to understand what's going on. However, as a communications and awareness-raising instrument, the EF appears to be doing its job".

"The question is, whether some single index is capable of measuring such multi-facetted issues. However, when some indicator aspires to do that, it can put the indicator into the dispute".

"For speedy communication and 'shock factor', and also to demonstrate global equality issues; no because risk of misinterpretation and because more precise indicators needed for better planning, management and policy-making".

In terms of remaining focused on the goal of the Ecological Footprint there was also support for aggregation for communication purposes.

"Aggregation useful for communication and this should not be lost".

Finally, many of the respondents answered the question by stating that it would be desirable but is simply not possible.

"Of course it would be great but I don't think it is feasible".

A1.10. Response to Question 6: Applicability of the Ecological Footprint to measure WWF's Footprint Goal

Over 70% of the survey experts believed that the Ecological Footprint was inadequate as a measure of progress and therefore suggested that WWF's goal had little meaning without further goals and indicators to supplement the Ecological Footprint.

Despite many people highlighting the limited nature of this goal, some did recognize that the goal was intrinsically linked to the Ecological Footprint; therefore the indicator had to be used to measure this goal.

"If the goal is to assess the progress using the EF explicitly, than it is the relevant indicator for achieving this goal".

The absence of any economic and social concerns within this goal was mentioned by many.

"You would require a number of other complementary indicators to ensure that 'natural resources are able to sustain life' in perpetuity e.g., social/economic and environmental".

As with many questions, most of the experts did not see the Ecological Footprint as anything more than a communication tool, therefore suggested that as a goal that requires some form of accurate measurement, it is completely inadequate. Comments by experts supporting this include:

"I do not find the footprint measure meaningful except as an illustrative heuristic".

"It is one indicator that helps to frame the debate, but there are still methodological issues with the approach".

"Again, nothing wrong to have a vision and communicate this—but needs to be underpinned by more than EF. Perhaps ok to use it as an indicator, 'indicating' progress (or otherwise)".

In conclusion, further evidence needs to be provided by WWF on the precise meaning of the goal before appropriate indices can be selected.

A1.11. Response to Questions 7–9, 12–15, 18 + 19: Application to Policy Formulation

As the Ecological Footprint can provide a strong communicative message of over-consumption, it does have a policy role and this is to inform the general public, politicians and decision makers on the issue of ecological overshoot resulting from either inefficient production or excessive consumption. There were also suggestions that as a communication goal the global equity issue was strongly visible within the Ecological Footprint (compare to [42]).

Beyond this important task, nearly all the experts believed that the Ecological Footprint had no further policy application. In this respect they were referring to the testing of different policies within a policy formulation process. Within such a framework the logical starting point is the identification of environmental problems. It will always be very difficult to establish whether climate change is more important than ecotoxicity or biocapacity constraints. While evidence can be used, such as the potential to cause human suffering and irreversible damage to ecosystems, this will always be for some level of subjectivity in the decision making process.

Some experts have the perception that the Ecological Footprint is the best indicator available to measure human appropriation of biocapacity. Therefore, if this is the policy question it is clear to see how the Ecological Footprint could be selected as the indicator to monitor this purpose. Many of the experts were clear that on other environmental issues, the Ecological Footprint would not be the chosen indicator to demonstrate progress in this area within a policy context, expressed by the quote below.

"When one single method addresses too many issues, none of which would be addressed adequately".

The Ecological Footprint's ability to demonstrate the impact of substances, materials/products and key flows is perceived to be debatable. Again, the issue of communication was mentioned by the experts who thought that the Ecological Footprint value stopped at the first stage of communicating the issues.

"It is conceptually simple and useful from a heuristic and pedagogical perspective".

"A footprint in itself can provide little policy information".

"Useful in communicating urgency to do something about current consumption and production systems, and communicating unequal share of 'environmental space'"

"It is largely useful for awareness raising and communicative purposes in general".

However, as covered in more depth in the methodological review section, there is concern that the Ecological Footprint does not cover the issue that it refers to with enough rigour to be applied to the policy process outlined above, as expressed by one of the experts:

"Because the EF is not conceptually robust, it should be abandoned except as a heuristic (e.g., One Planet Living is a useful idea, but the EF is not a good measure either of whether it is being achieved or of progress towards it)".

Putting this issue aside, the experts were asked which initiatives/developments would help to strengthen the ability of the Ecological Footprint indicator to inform policy making. They were given a range of options and the opportunity to express their opinion. Figure 4 below highlights the results from the options that were given.

Three key areas of development were highlighted. Firstly, many of the experts thought it was valuable to use the most appropriate method for the required question. This does raise issues relating to standards and the ability of standards to reflect this required diversity. In addition to this, building Ecological Footprinting into a recognized accounting system was seen as essential. As well as receiving a high number of votes there were also numerous comments made about the UN System of integrated Environmental and Economic Accounting, UN SEEA [43].

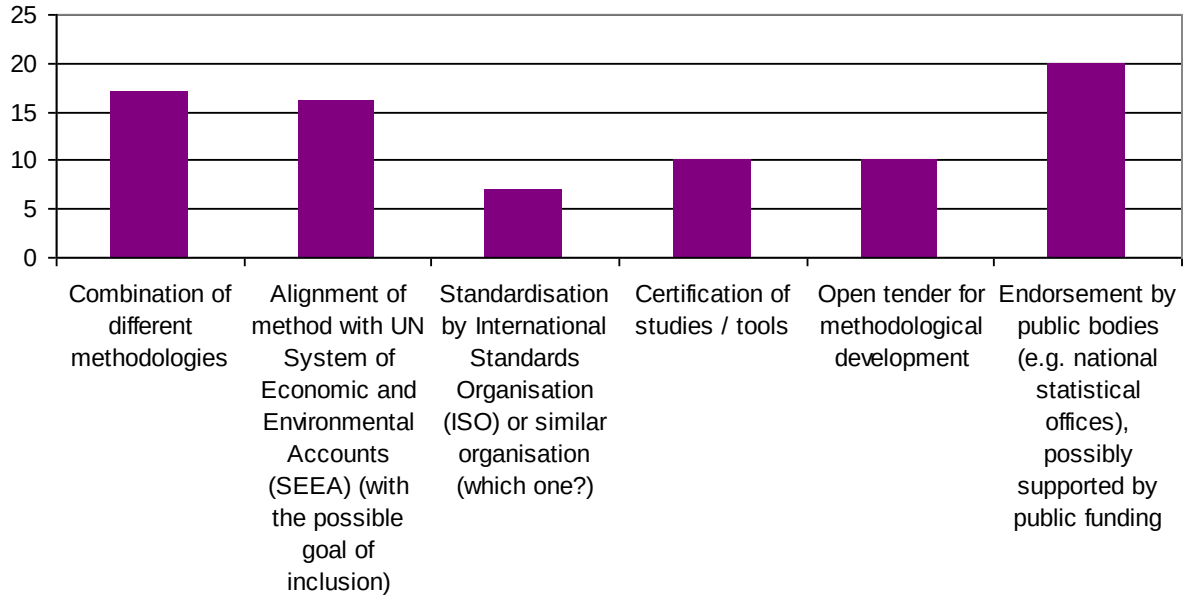
"Most important points are: use the EF in combination with other complementing approaches and better link the EF to environmental accounting standards".

"Coming closer to the SEEA/NAMEA standards is key for further success of the EF in some areas, such as statistics and official environmental reporting".

"EF accounting should be compatible [with] the UN System of National Accounts and GDP/GNP indicators, in terms of system boundary and scale, in order to facilitate comparative analysis".

"It should reflect the SEEA (System of Integrated Environmental and Economic Accounts) and related issues".

Figure 4. Response to initiatives/developments that would help to strengthen the ability of the Ecological Footprint indicator to inform policy making.



In addition to this, the endorsement by public bodies was seen as extremely important. Again, the issue arising as "endorsement of what", *i.e.*, would it be endorsed for the answer of a specific research question. Without this it is difficult to see how any indicator could be provided an endorsement.

Finally, it is widely acknowledged that any model that can provide scenarios of what is likely to happen under present or alternative policies is a valuable tool. Increasingly, scenarios are being used by governments to ensure that they are moving into a more sustainable direction, even if this progress is slow.

Therefore, it would be useful to have in place an accounting tool that can provide a scenario of a sustainable future and goes beyond highlighting unsustainability in the past. In terms of the survey experts opinions as to whether the Ecological Footprint could provide scenarios, there was an overwhelming opinion that it could not.

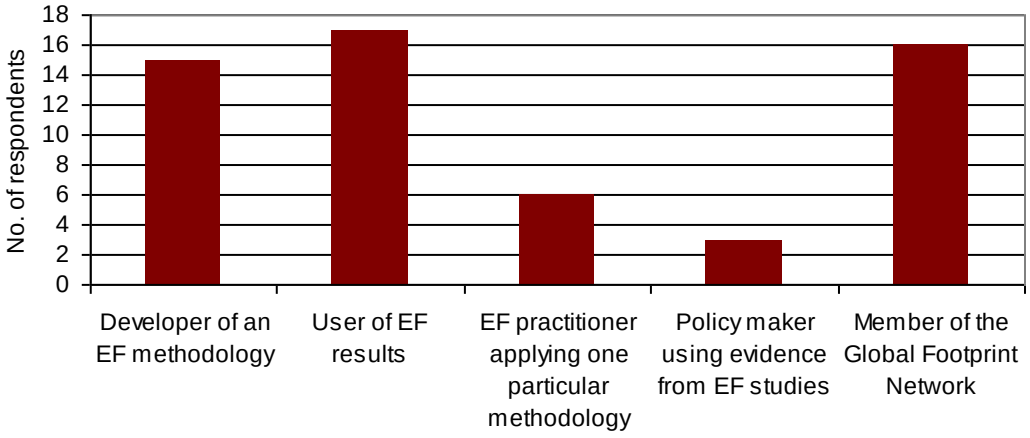
"It is also important to note that as an indicator it is 'yesterday's news' we are reporting on; it tells us little about what might happen in the future under different development scenarios".

"The EF is inherently about current and past consumption patterns, not about future impacts, but again, if scenarios can be modeled as to what impacts future consumption might have, this could be extremely useful to policy makers".

A1.12. Response to Question 20: Involvement with the Ecological Footprint

Respondents described themselves as:

Figure 5. Response to question about personal involvement with the Ecological Footprint.



Appendix A2. Full Review of Methodological Options for the Ecological Footprint

Scope of Work

This section reviews recent methodological developments with respect to the Ecological Footprint and evaluates the key approaches against the criteria that were identified as important and relevant in the survey described above. In order to determine the policy relevance and robustness, methods were examined in the light of their credibility and consistency, availability and state of implementation, usefulness and relevance of the results, as well as data quality and availability.

The literature review focuses on the description of EF methods in the scientific literature, namely articles in peer-reviewed journals and academic working papers and research reports (grey literature), and collates them into groups of methods. As the review is supposed to cover the whole range of possible EF methods, no particular selection of literature was applied.

In recent years the methodology for calculating the Ecological Footprint has been further developed and many variations and enhancements have been described in the literature. It is impossible to describe all of these approaches individually and therefore we have clustered them into the following broader categories of methodologies:

A. Conventional Ecological Footprint Accounting
B. Variations of the conventional method (non input-output based)
C. Dynamic Ecological Footprint models
D. Input-output based methods

What follows is a brief description of major characteristics and developments under each category with ample references to original literature for further reading.

A: Conventional Ecological Footprint Accounting

The Ecological Footprint is an indicator that aims at measuring human demand on biological resources and setting it in relation to the regenerative capacity on Earth. The current definition provided by Global Footprint Network (GFN) is: "The Ecological Footprint is a measure of how much biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates using prevailing technology and resource management practices. The Ecological Footprint is usually measured in global hectares. Because trade is global, an individual or country's Footprint includes land or sea from all over in the world. Ecological Footprint is often referred to in short form as Footprint (not footprint)" [44].

National Ecological Footprint accounts (NFA) use 'global hectares' as the unit of measurement [45]. A global hectare (gha) is defined as "the annual productivity of one hectare of biologically productive land or sea with world-average productivity…" [44]. Yield factors and equivalence factors are used to convert the actual physical area (hectares, ha) into global hectares. Whilst this procedure is supposed to guarantee international comparability, it comes at the loss of locally important information on the management of natural resources [46].

The innovative work by [40], [47] and [48] is the basis upon which the calculation of national Ecological Footprints is based to the present day. The National Footprint Accounts (NFA) provided by Global Footprint Network (GFN) follow in principle the original accounting procedure, although several modifications have been introduced over the years. Significant publications are [45,49-58] and, most recently, [8] and [59]. A generalized mathematical formulation of conventional Ecological Footprint calculations can be found in [46].

In principle, the NFA use data from the United Nations Food and Agriculture Organization on domestic production, imports, exports and yields for a number of primary and secondary products from agriculture, forestry and fisheries, in order to calculate the apparent net consumption of a nation and the associated appropriation of land. A considerable share of the Footprint consists of the notional

forest area that would be required to absorb carbon dioxide emitted from the combustion of fossil fuels. The domestic national energy Footprint is calculated via CO_2 emissions data from International Energy Agency (IEA, Paris, France). Non-fossil-fuel technologies for electricity generation, e.g., hydro power, are covered by their direct land requirements only; nuclear power is no longer treated as equivalent to fossil-fuel-generated power [59]. For the trade balance of manufactured products, embodied energy data from disparate sources are used to convert their quantities into energy equivalents (for a discussion on the Footprint of trade is calculated see [36]).

The Ecological Footprint of consumption calculated in this way can then be compared to 'biocapacity' as a measure of available biological resources. According to GFN, biocapacity is the amount of "land and water that supports significant photosynthetic activity and accumulation of biomass…" [8]. As for the Footprint, these land and water areas are adjusted for their productivity to derive global hectare units.

Our evaluation of the conventional EF method refers to this bioproductivity-based NFA approach and its main applications. The latest suggested modifications to the NFA method are described in [30].

The key application of this method is certainly the bi-annual publication of National Footprint Accounts and accompanying information in WWF's Living Planet Report series [the latest one being 34], (see also [60]). There are countless other applications of the conventional EF concept. We have compiled a list of publications in peer-reviewed journals, which covers many but not all papers and does not include the numerous reports and publications from the grey literature ([47,48,61-107]).

One of the key criticisms of the conventional EF method—amongst numerous others—is the apparent inability to show unsustainable use of forest land, crop land, marine and inland fisheries, or pasture land biomes on a global level due to the nature of the calculations [12] and because it fails to distinguish between sustainable and unsustainable yields [31-33]. The EF of domestic extraction (domestic production of goods) equals per definition the biocapacity of the system (Erb elaborates extensively on intricacies of the yield assumptions, in particular in forestry [108]).

A good example is the treatment of marine biocapacity and Ecological Footprint in the NFA. In order to aggregate and compare fish, primary production is used. On the Footprint side, all fish produced is converted into the amount of primary production required to support this fish (based on the trophic level of the fish) and then the world yield for the amount of harvestable primary production per average ha of marine continental shelf is applied. This harvestable amount of primary production is estimated as the amount of primary production which can be sustainably removed from the ecosystem. On the biocapacity side, the yield factor reflects how much primary production a nation has on the continental shelf *versus* the world average. Because of this approach, biocapacity is not actually a measurement of the amount of fish stocks remaining, instead it reflects the amount of productivity available in that ecosystem [8,109].

The problem is estimating the very amount of fish that "can be sustainably removed from the ecosystem". In the most recent NFA for the UK, the marine Ecological Footprint is around 16% of marine biocapacity in the UK [110]. However, reports on overfishing in the North Sea appear contradictory to these results. On the global level, fishing grounds are not to be shown in overshoot either, with 0.17 gha/cap world marine Ecological Footprint *versus* 0.09 gha/cap world marine biocapacity. Again, this finding is in stark contrast to the results from a recent study showing that many marine ecosystems are facing mass extinction as a result of human activity, such as habitat

destruction, acidification of sea-water and overfishing. Jackson's [111] review into the regions and species most at risk suggests that up to 90 per cent of large predatory fish stocks have disappeared, transforming complex food webs into simplified ecosystems dominated by microbes and algae. The study concludes that there has been drastic and rapid degradation of marine ecosystems over the last few decades. Hence destructive exploitation can take place over extended periods of time without the Ecological Footprint flagging up as demand still remains below the apparent ecosystem productivity or biocapacity.

B: Variations of the Conventional Method (non input-output based)

There are numerous variations of the traditional, bioproductivity-based EF method.

Actual land units/local yield factors

Many authors chose to omit the weighting with yield and equivalence factors in order to reflect actual local, rather than hypothetical global average conditions. Studies where the Ecological Footprints is expressed in actual physical hectares of land used, rather than in global hectares, or in both units, include [108,112-118]. When using local yields for primary biological products instead of global yields, results can differ by a factor of two or more. The authors in [46] compare the two unit systems, point out methodological inconsistencies in the gha metric and discuss policy implications. It is in particular the conversion to world-average productivity in the conventional approach where much information about regional land degradation and the sustainability of regional land management practices is lost.

Land disturbance

Another modification was introduced by Lenzen and Murray [9] who measure the current and projected future land disturbed because of human consumption of biotic and abiotic resources (food, timber, minerals *etc.*), and emissions of all greenhouse gases from all sources. Land disturbance is expressed in "disturbed hectares", calculated from actual areas by weighting with factors describing the deviation of the biodiversity of vascular plants from a pristine condition. This approach therefore establishes a link between local land management practices, biodiversity and consumption patterns elsewhere, thus adding crucial information to policy for long-term planning. Lenzen *et al.* [33] point out that important global issues such as land cover disturbance, soil degradation and biodiversity decline are not covered in the bioproductivity research question and metric and that this omission "may actually provide incentives that lead to future problems". As an example Lenzen and Murray [9] refer to countries such as Brazil, Indonesia, Australia or Malaysia with extremely high land clearing rates for which the bioproductivity-based approach shows ecological remainders. The Ecological Footprint can hence not indicate certain severe detrimental impacts on biodiversity and ecosystem health.

Net primary productivity (NPP)

NPP is the net amount of carbon assimilated in a given period by vegetation; it tracks the net flux of carbon from the atmosphere into green plants. About a quarter of potential net primary productivity is appropriated by human activity for the purpose of harvest (53%), land-use-induced productivity (40%) or human-induced fires (7%) [119]. From an ecological perspective, the Human Appropriation of NPP (HANPP) is defined as the difference in the amount of NPP that would be available in the absence of human intervention and the fraction of NPP remaining in ecosystems after human harvest under current conditions [120]. The concept of HANPP has therefore the potential to go beyond the simplified EF approach by linking socioeconomic activities to the impacts of land use and to ecosystem functioning.

Venetoulis and Talberth [12] recognize this potential and propose several methodological and theoretical refinements based on the use of net primary productivity (NPP) rather then bioproductivity; an idea that originated in the publication by Vitousek *et al.* [121]. The modified approach from Venetoulis and Talberth [12] includes all land and water area on the Earth as part of biocapacity, arguing that areas that are not directly productive for human purposes (tundra *etc.*) also have an important role in generating global biocapacity or supporting critical ecosystem services [41]. In order to account for the protection of biodiversity, they set aside a portion of biocapacity in each biome for other species based on recent global hot spot and gap assessments. They change the basis of equivalence factors from agricultural productivity potential to NPP, and change the way in which carbon sequestration rates and the resulting Footprint are calculated. In their approach multiple land uses are possible, e.g., a hectare of forest can absorb carbon dioxide and produce paper. Using this adapted approach, Venetoulis and Talberth [12] construct Ecological Footprint accounts for 138 countries between 1961 and 2001 and compare their results with the bioproductivity-based National Footprint Accounts of GFN. At a global level, both biocapacity and Ecological Footprints are considerably larger when using NPP. In addition, using NPP shows ecological overshoot (negative ecological balance) for crop land, built space, marine and inland fisheries and energy land whereas the bioproductivity based EF reports overshoot only with respect to energy land. This ability to demonstrate ecological overshoot in general is advantageous when indicating particular problems not associated with carbon dioxide emissions. However, the approach currently stops short of defining the sustainable use of NPP. Establishing sustainable yield benchmarks, as recommended frequently in EF literature, would clearly be the critical advance of any EF method. The NPP-based method opens up the possibility of implementing this in the future (Venetoulis and Talberth [12] quote the example of agriculture: "…organic agriculture methods retain considerably more NPP and, in a recent long-term study, have been shown to reduce crop yields by roughly 20% but enhance long-term soil fertility and biological diversity").

Haberl *et al.* [122] compare the bioproductivity-based with an NPP-based EF approach and discuss the research questions driving each of them. They suggest that the two approaches serve different functions. The conventional EF method measures humanity's utilization of biologically productive area and is useful to compare the resource consumption profiles of different human populations. Human appropriation of NPP on the other hand maps the intensity of socio-economic use of ecosystems in a spatially explicit manner [119]. Combining the two methods by integrating NPP into

the EF framework, as done in [12] can thus provide an explicit link between human consumption and ecosystem services. This has been supported by the concept of embodied HANPP (eHANPP) which links net primary production in one region with a particular level of biomass consumption in another region by taking into account trade in biomass [28]. Conceptually similar to the virtual water approach, eHANPP can provide additional insights on the impacts of biomass production and consumption chains on ecosystem energetics [29].

Furthermore, some empirical and conceptual studies have investigated and established the link between NPP and biodiversity [123-127]. The results support the species-energy hypothesis, thus confirming the notion that HANPP could be a useful pressure indicator for biodiversity loss. The further exploration of these findings would have a high potential for the EF-NPP method as a removal (or overuse) of NPP would show an associated decline in biological diversity—a feature that would make the *Ecological* Footprint live up to its name.

Emergy

The emergy concept stems from general systems theory and systems ecology and is based on the second law of thermodynamics. Emergy is defined as the availability of energy (exergy) of one kind that is used-up in transformations directly or indirectly to make a product or service [128,129]. Emergy translates the energy flow from solar radiation into renewable resources, including surface wind, physical energy of rain on land, chemical energy of rain on land, physical stream energy, waves absorbed on shores, earth sedimentary cycle, agricultural, forest, pasture and fishery products, as well as non-renewable resources, mainly fossil fuels and measures them on a common basis expressed in the unit emjoule.

In recent years, several researchers, mostly from China, introduced emergy analysis to modify the basis of EF calculations. Zhao [130] present a method based on emergy, in which the human consumption corresponding to six types of basic bioproductive areas are translated into a common emergy unit and the emergy-based EF and carrying capacity are defined and calculated through a case study of the Gansu province of China in 2000. Chen and Chen [10] extend on this concept and compare the bioproductivity EF method to an emergy-based method in a time series (1981–2001) study of the Chinese society (represented in [131] as a method based on embodied exergy). The required 'transformities' of products and services are taken from previous studies in both cases ('transformity' is defined as the amount of emergy required directly and indirectly to generate a unit of energy in unit of solar emjoule per joule (sej J^{-1}), which constitutes the ratio of emergy to available energy ([132], p. 156). This, however, seems to be the critical bottleneck of the method; 'transformities' would have to be generated and updated regularly in order to provide a robust data basis for the approach and currently this is lacking.

Liu *et al.* [132] also use emergy analysis to calculate both, ecological capacity and Ecological Footprint of cropland in a time series case study of Jiangsu Province, China and compare the results to the conventional EF.

Authors of the emergy-based method point out that all areas of land are considered and that no indirect weighing system is used to translate different pressures into an amount of land (as is the case in the bioproductivity-based EF method). Emergy-based footprinting avoids the "controversial topic of

yields in the calculation of energy footprints" ([130], p. 74) and it is not necessary to consider equivalence factors [132].

The emergy concept is based on systems theory and system ecology and provides a link to geophysical and biological processes on Earth. It adopts a holistic earth system view. According to ([10], p. 112) it is a "unified thermodynamic metric for objectively evaluating resource depletion, environment degradation and ecological overshoot…". As a major advantage of emergy analysis the possibility of measuring resource use of ecosystems is mentioned ([130], p. 74). The practical usefulness of the method, however, is questionable. The complexity of ecosystems will always make calculations of transformities difficult and uncertain. There is no single transformity for any class of product or process and each production pathway for any given product represents a unique transformation process that will result in a different transformity. Zhao *et al.* ([130], p. 74) acknowledge that this will affect the reliability of conclusions at high levels of detail. Furthermore, emergy calculations do not take into account land productivity and are therefore not able to indicate an overuse of land-based production.

Other authors also present emergy-based calculations and indicators and make comparisons to the bioproductivity-based EF, e.g., [133] and [134]. Siche and colleagues [135] suggest that the combination of Ecological Footprint and emergy analysis, as proposed by the Chinese authors above, would result in an improved sustainability index (see also [136]), [11]. Furthermore, they propose to consider the value of Net Primary Production (NPP) in emergy units (seJ m^{-2} $year^{-1}$) as a basis for the calculation of EF equivalent factors [137].

Including further emissions and resource uses

Various modifications have been suggested to include emissions and resource uses other than the standard ones in the conventional EF method.

[9] consider greenhouse gases other than CO_2 and emission sources other than energy use, such as land clearing, enteric fermentation in livestock, industrial processes, waste, coal seams, venting and leakage of natural gas, *etc.* Non-CO_2 emissions are converted into units of carbon dioxide equivalent using the respective global warming potentials. They then introduce a new land category, called 'emissions land', for which they consider the projected disturbance of terrestrial and aquatic ecosystems due to climate change and sea level rise under doubled CO_2 equilibrium conditions. The authors concede that the resulting figures should be taken as a crude approximation due to the substantial uncertainty in predicting impacts of climate change on land. They argue, however, that their method provides "better options for greenhouse gas assimilation, varying between regions owing to differences in geographical, climatic, and technological circumstances. Increases in energy efficiency, fuel mix and structural economic changes, renewable energy sources, and reforestation are existing alternatives for compensating emissions" and can be taken into account by using the 'emissions land' approach based on land disturbance ([9], p. 249).

Peters *et al.* [6] add toxic pollutants into this concept. Pollution is also included in a modified EF model presented by [138] who undertake an extended ecological assessment of the Pearl River Delta urban agglomeration in China in 2005. Venetoulis and Talberth [12] suggest that the relationship

between net primary productivity (NPP) and concentrations of toxins, such as radioactive or heavy metals, in a biome may help to derive methods for expanding the scope of EF analysis.

Walsh *et al.* [139] present and discuss in detail several ways of incorporating methane into Ecological Footprint accounting. These include a) the translation of CH_4 into carbon equivalents (with and without accounting for the larger GWP of CH_4) and subsequently attributing a sequestration area as in the conventional EF approach, b) estimating the area required for the oxidation of methane by microbial activity in soils and c) accounting for the radiative forcing of methane and the quantity of additional land required to dilute its greenhouse effect. As all approaches lead to significantly different results it will depend on the choice of methodology as to how much weight methane (and generally non-CO_2) emissions should receive in the aggregated EF indicator.

In addition to CO_2, Holden and Hoyer [5] include CH_4, N_2O and even NO_x in EF calculations of fossil fuels by taking into account their global warming potential and treating the total greenhouse gas equivalents as if they were the CO_2 that is to be assimilated by (notional) forests. The authors use the Norwegian assimilation rate of 1.58 t CO_2 per forest hectare. Furthermore, they include acidifying emissions (SO_2 and NO_x) by accounting for the land area required for the safe deposit of sulphur and nitrogen, *i.e.*, they employ the concept of critical loads (for acidity) to convert emissions into the land area required to keep acidity below critical levels. Results are reported in local, actual hectares, not global hectares.

The study of Nguyen and Namamoto [7] incorporates non-renewable or abiotic resources as an additional EF category. The resource scarcity of non-renewable resources is evaluated on the basis of a thermodynamic approach which uses exergy loss as an indication for the decrease in resource potential functions available for future generations (exergy is defined as the useful energy available that can be fully converted into other forms of energy, especially to perform work). The exergy loss due to the utilization of non-renewable resources is converted into a notional surface area that would be required to absorb an equivalent amount of solar energy to compensate for the loss of exergy. The authors present a case study for thirteen commonly used metals and seven countries and compare their result with those from conventional EF calculations, finding that their modified EF is between 9% and 123% higher. In conventional EF calculations the CO_2 emissions associated with fossil fuel energy use in the mining and manufacturing of metals would lead to a notional forest area required for sequestration. However, Nguyen and Namamoto [7] do not compare this directly with results from their exergy-based approach.

C: Dynamic Ecological Footprint Models

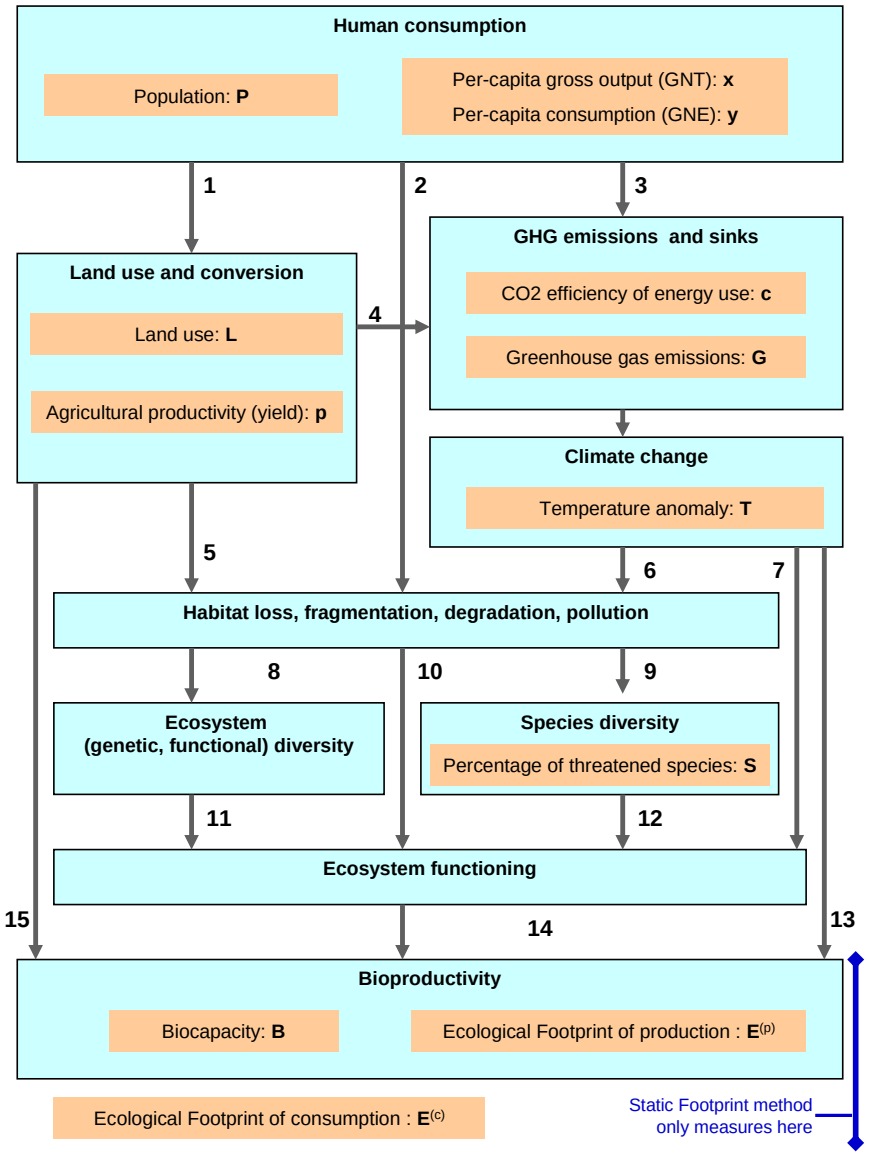
The Ecological Footprint is meant to indicate an overuse of natural biological resources (called "overshoot") by human consumption [40]. By definition it accounts for human demand on global bioproductivity but does not include actual impacts on ecosystems and biodiversity, linkages along causal chains or any temporal aspects.

There is, however, substantial evidence that in the long term, diminished ecosystem functioning will deteriorate the services humans are able to derive from natural and artificial landscapes, for example agricultural bioproductivity. Ecosystem functioning, in turn, is influenced by a multitude of impact pathways, amongst which the perhaps more prominent involve land use and conversion and climate

change [140-144]. In 2001 already, ([9], p. 250) wrote about the Ecological Footprint: "A truly comprehensive assessment would have to employ a decomposition of impacts according to driving factors, and consider the nature and causes of problems, as well as economic, political and climatic constraints on their solutions".

Lenzen *et al.* [13] have presented a profoundly different concept of a Dynamic Ecological Footprint (DEF) method for forecasting and policy analysis that could become a complementary tool to the conventional method. The approach links causal pathways from human consumption to bioproductivity and is anchored in ecology by incorporating biodiversity variables (see Figure 6). It allows for a temporal analysis of country-level consumption, production, land use, greenhouse gas emissions, species diversity, and bioproductivity up to 2050. In this view, human consumption exerts the pressure, acting via land use and greenhouse gas emissions to biodiversity and ecosystem functioning, with bioproductivity being the end-point of impacts, or state. To close the loop, available bioproductivity (biocapacity) will in turn limit what humans can consume.

Figure 6. Impact pathways and variables linking human consumption, bioproductivity and the Ecological Footprint in a dynamic concept (adapted from [13]).



The methodology is described in full detail in [13]. What follows is a very brief description based on [145]. As in the conventional, static EF method, most of the raw bioproductivity data comes from FAO statistics (for all other data sources see [13]). Initial data are then updated every year based on the influence of economic output, population, change in productivity and energy/emissions efficiency for each country. The productivity of land is influenced by land degradation, technology (e.g., genetics, better management *etc.*), the effect of biodiversity and temperature changes due to GHG emissions. CO_2 emissions from land clearing are modeled using emission factors which take into account burning of above ground biomass, post burning regrowth, decay of above ground biomass and below ground carbon storage. Some of these processes occur over 25 years. CO_2 absorbed from forest growth is calculated based on the change in natural forest and plantations. The effect of GHG emissions on climate change is calculated for the whole planet, taking into account the different global warming potentials and decay rates of CO_2, NH_4 and N_2O. Species diversity is influenced by change in land use and climate change. Finally, biocapacity and Ecological Footprint are calculated based on land use area, productivity and yield. All the relationships in the model are additive, *i.e.*, it is assumed that e.g., the effect of population can be added to the effect of productivity *etc.* to get a total change in land use required.

The Dynamic EF model is based on a multi-region input-output analysis of more than 200 countries, albeit assuming 1-sector economies. Embodied impacts of trade that can be quantified and modelled include Ecological Footprint by land type, biodiversity (numbers of threatened species) and GHG emissions. DEF is very similar to the climate impact models used in the IPCC framework where GHG emission scenarios are translated into global temperature change. DEF is however fundamentally different from projections of non-linked individual components of the Ecological Footprint as described in [146]. There, the components of biocapacity and EF do not depend on each other and are projected individually. Therefore, no actual interdependencies or feedback loops can be modeled.

The DEF concept presented by Lenzen and colleagues [13] is a further development of a previous dynamic model described by [117]. These authors based EF calculations for the period 1975–2100 and for 17 world regions on IPCC SRES emission scenarios. However, no dynamic linkages to ecosystem functioning was implemented in this model.

The preliminary analysis by [13] demonstrates the potential capability of a dynamic approach, by collating a wide range of global country-level data, and applying state-of-the-art analytical techniques such as multi-region input-output analysis, multiple regression of spatial lag models, temporal climate modeling, Monte-Carlo simulation, Structural Decomposition Analysis, and Structural Path Analysis. The new approach is meant to be complementary to the existing, static Ecological Footprint method in that it is aimed at answering the question of how today's human activities contribute, through their particular land use and emission patterns, via habitat and biodiversity loss, and impaired ecosystem functioning, to future bioproductivity decline. A dynamic, causal method thus opens up new policy areas amenable to Ecological Footprint analysis, such as the investigation of agricultural practices, land disturbance, or species threats. The static, end-point method is not sensitive towards these pressures.

One important characteristic of the DEF is that does not show an 'overshoot' situation. This is because the resulting Ecological Footprint is always smaller than the available biocapacity on Earth. Instead of calculating the notional area needed to sequester CO_2 emitted currently (according to the

conventional EF representing an area greater than can be provided within the biosphere), the DEF method allocates the actual impact of CO_2 emissions to changes in bioproductivity due to future climate changes. Walsh *et al.* [139] comment on the Dynamic EF method: "The impact in this sense will be the future degradation of biocapacity due to likely climatic instability. In actuality we cannot use more land area than currently exists; therefore overshoot will be evidenced by the convergence of the actual ecological footprint with available biocapacity". It is the narrowing of the gap between EF and biocapacity in the DEF method which is of concern to future sustainability.

It should be mentioned at this point that EF calculations are based on stock and flow accounting. Therefore, overuse of stocks, e.g., in forestry, will create overshoot in EF methods. The convergence argument holds only true with annual plants, not with perennials. Furthermore, biocapacity is not a static entity but dependent on technological change. Historically, technological improvements have overcome limitations on capacities. Therefore, the acknowledgement of technological change and of dynamic (not static) biocapacity is possibly the most stringent part of the DEF concept.

Apart from [117] and [13] no other attempts of calculating and projecting Ecological Footprints in a dynamic model have been reported in the literature and applications that are relevant for policy or decision-making have yet to be carried out. Noteworthy is the approach of Grazi *et al.* [147] who present a theoretical dynamic framework to analyze the impact of spatial configurations of economic activities on the (un)sustainability of the economy in the long run. The result is a dynamic economic theory of what they call 'spatial sustainability', a concept referring to spatial configurations and dynamics that are consistent with environmental sustainability in the sense that resource use and pollution are within the assimilative capacity. This dynamic approach can help to formulate policies focusing directly on emissions reduction, redirecting trade or spatial reorganization. It is a further development of a static method that has been compared numerically to the Ecological Footprint with the conclusion that "…the EF is not a reliable guide to spatial sustainability" ([148], p. 152).

D: Input-Output Based Methods

Environmental Input-output Analysis (Environmental IOA) is a macro-economic top-down technique that uses input-output tables, which describe the monetary transactions between sectors, in order to determine the life-cycle impacts of certain final demand categories such as domestic consumption and exports. It does so by linking environmental pressure indicators such as emissions, land use, water use or Ecological Footprint of production with all sectors in a national economic system that describes all transactions, including imports, throughout this economy. Inputs to each industrial sector and the subsequent uses of the output of those sectors are separately identified.

IOA has its origins in economics, but Leontief [149], who pioneered the work in the development of IOA, already intended to incorporate social and physical facets in the analyses (in 1973, Wassily Leontief received the Nobel Prize in Economic Sciences for the development of the input-output method and for its application to important economic problems). The use of IOA for life-cycle applications is very common, first focused on energy studies in the 1970s and 1980s and later on in more general environmental applications.

Given that the focus of the Ecological Footprint is to capture the total (direct plus indirect) resource use embodied in final consumption in an economy, input-output based models seem to be the ideal

accounting framework. The primary function of input-output analysis is to quantify the interdependence of different activities within the economy. It uses straightforward mathematical routines to track all direct, indirect and, where appropriate, induced, resource use embodied within consumption. Input-output analysis is in most cases based on monetary information which entails specific assumptions and limitations as, for example, mentioned in [150]. For the discussion about monetary *vs.* physical IOA we refer to the literature, e.g., [115,151-154].

Single-region input-output models

In IO-based studies on consumption, which include total environmental pressure over the whole supply chain of products, it is often assumed that imported goods and services are produced with the same technology as the domestic technology in the same sector. Lack of data or resources to distinguish differences in the production technologies (and therefore Footprint intensities) of trading partners is the most common reason for adopting this assumption. IO models of this type are referred to as single-region input-output, or SRIO, models.

SRIO models have been applied to Ecological Footprint analysis for over a decade ([112,115,116,153,155-162]). Single-region IOA is now a well established technique for the calculation of Ecological Footprints of:

- nations [9,161,163];
- sub-national entities [116,164-178];
- socio-economic groups [173,179,180];
- and organizations or companies [181-183] (see also the review by [184]).

Over the last decade in particular there has been a tremendous increase in applications of analytical, and indeed forecasting, models based on environmentally extended input-output techniques. Besides being scientifically well described and established, the crucial advantage of IOA is that it is possible to attribute environmental impacts to virtually any consumption activity, such as consumption of regions, nations, governments, cities, socio-economic groups or individuals, whether domestically or abroad (imports/exports); to virtually any production activity of organizations, companies, businesses, product manufacturing, service provision *etc.* and to virtually any associated economic activity in between such as supply chains, trade flows or recycling.

Applying the input-output method to an Ecological Footprint basically involves populating a matrix of biological resource use and yield coefficients for each economic sector. The data can either be compiled from scratch, e.g., from FAO statistics or from an existing account of a national EF of production. Such an approach is described in [161] who reconcile the National Footprint Account of the UK—in terms of bioproductivity—with the UK economic national accounts.

There are two key advantages of employing an IO framework to Ecological Footprinting. First, it provides a transparent, unambiguous and consistent allocation of impacts from production to consumption, bringing it fully in line with the System of National Accounts (SNA) [185] and the System of integrated Environmental and Economic Accounts (SEEA) [43] purported by the United Nations. The UN-SEEA handbook presents environmental IOA as one of its tools. The IO-framework is widely accepted in national environmental accounting in relation to environmental impacts of

consumption and trade. Several statistical offices—e.g., in Denmark, Netherlands, Germany and Sweden—have used this approach. The method is transparent and replicable, widely used and well documented. Therefore, IOA can also help with the standardization of EF accounting. Many issues that come up in the ongoing EF standardization process have already been addressed in the environmental accounting and life-cycle analysis communities.

The second key advantage of IO-based EF accounting lies in the vast array of possible applications, especially on the sub-national and corporate level. Here IOA helps to solve two specific problems that arise when trying to calculate Ecological Footprints for use in decision-making in the public and private sector: (a) lack of data and (b) comparability of results [161]. Thanks to standardized national accounting in most economically important countries, there is sufficient data on consumer and other final demand expenditure to allow for a detailed disaggregation of national Footprint estimates by economic sector, consumption category, sub-national area or socio-economic group, whilst ensuring full comparability of results. Standardized economic national accounts provide a reliable basis for input-output data, although there is a publication time lag of up to several years, depending on the country. Mechanical procedures for updating data or estimating missing data have been described in the literature, see e.g., [186-190] and references therein. Main international data sources are Eurostat (http://epp.eurostat.cec.eu.int), OECD (http://www.oecd.org/statsportal) and GTAP (http://www.gtap.agecon.purdue.edu). Taking the mutual interrelationship among economic sectors into account, IOA then assigns direct as well as indirect Ecological Footprints to consumer activities that are relevant for sustainable consumption policies.

Another advantage is that IO-based approaches bring Ecological Footprint analysis into the scope of ecological-economic modeling frameworks and enable dynamic scenario analyses. These are essential for a systematic evaluation of policy options and are at the heart of today's sustainability appraisals.

Employing input-output analysis does not actually create a new EF method. Especially when starting from conventional, bioproductivity-based accounts of production Footprints (as described in [161]), all the EF-specific data, assumptions and parameters don't change. It is only the allocation of impacts to consumption activities and also to a nation's imports and exports where differences occur (see below for a discussion about the issue of trade). The main advantage of IOA lies in its unambiguous and consistent accounting of all upstream life-cycle impacts and the good availability of expenditure data that allow a fine spatial, temporal and socio-economic breakdown of consumption Footprints.

Multi-region input-output models

The SRIO approach does not enable a distinction of trade flows. Imports to one country always come from a number of different countries and world regions with different production technologies. Each of these regions also places import demands on foreign economies. Thus, Ecological Footprints related to the production in one country may by passed on far upstream in an international supply chain in the same way that inter-industry demands continue far upstream on the domestic level. These differences in regional production and supply paths cannot be modeled with a single-region framework. A multi-region input-output (MRIO) model becomes necessary where IO tables from several

countries are linked to each other via trade data to reflect interactions in an interlinked, multi-sector, multi-country economic system

A multi-region input-output approach for calculating national Ecological Footprints would be based on an account of annual amounts and yields of biomass used for human purposes by land type and industrial sector in each country or region [191]. The standard Leontief formalism then allocates these requirements to final demand, including domestic final consumption and exports, both satisfied by domestic production as well as imports [150,192]. Multi-region models are also able to capture feedback effects, which are changes in production in one region that result from changes in intermediate demand in another region, which are in turn brought about by demand changes in the first region.

Wiedmann *et al.* [193] present an overview of single- and multi-region input-output models used to assess environmental impacts of internationally traded goods and services and suggest that multi-region input-output models (MRIO) in particular could be used to calculate Ecological Footprints embodied in international trade (see also [191]).

Wiedmann [36] compares the conventional method to calculating EF embodied in trade flows, as implemented in the National Footprint Accounts (NFA), to an MRIO-based model. The differences in results on the commodity level by the two approaches are striking. As main factors causing the discrepancy the author mentions the omission of indirect emissions from traded energy commodities and trade in services (especially transport services) as well as the use of average carbon and energy intensity factors in the NFA method.

More generally, since the NFA only lists the total imports and exports from and to the rest of the world for each country and thus no trade supply chains are identified, no distinction can be made as to where or how the imported products are produced. Hence, no account is taken for differences in production technology in trading partners, or, specifically, the direct and indirect Footprint intensity of trade flows of goods and services (with trade in the latter, and associated Footprints, neglected all together) [36].

In the past, data availability, data handling issues and—to a lesser extent—the relative complexity of MRIO frameworks, have prevented a widespread implementation, but the situation is changing. In the last two years alone, a number of global or multi-national input-output-based trade models and analyses have been developed (see [36] for references). This is being accompanied by a slowly improving data situation. The most detailed and complete coverage of international IO data, including some environmental data, is currently the GTAP 7 Data Base compiled by the Center for Global Trade Analysis (https://www.gtap.agecon.purdue.edu/databases/v7). GTAP 7 has a base year of 2004 and contains 113 regions and 57 sectors. Large-scale research to improve the data basis for MRIO modeling is also under way in Europe in the EXIOPOL project which will eventually make the data and modeling basis for European focused analyses more consistent and accurate ([194], see also [195]).

Employing a MRIO model for national Ecological Footprint accounting in an international context would provide the following advantages [36]:

Using an MRIO approach would overcome inaccuracies in the intensities of resource use, energy and emissions of imported goods and services, since up-to-date, country-specific production factors

can be used and all international trade links—direct and indirect—are included. It would thus add accuracy and comprehensiveness to Ecological Footprint accounts of trade.

A MRIO framework is consistent with existing UN Accounting Standards [43] and it is desirable to develop it in parallel with the ongoing standardization of the Footprint methodology. This will underpin and lend credibility to a Footprint accounting standard. Attention should also be paid to retaining commodity classification as disaggregated and relevant for the Footprint as possible.

Using a model with a high sector disaggregation also allows for the tracking of international supply chains. Structural Path Analysis (SPA), an analytical technique that allows for the quantification of specific supply chain links, is well suited to extract and prioritize impacts from international chains of commodity groups and to link locations of consumption with hot spots of environmental impacts.

MRIO is also the only practically conceivable method for the comprehensive assessment of activities of multi-national corporations, since these essentially represent a production network spanning multiple sectors in multiple countries.

Finally, comprehensive economic-environmental input-output model systems are well suited to perform scenario simulations of the environmental and socio-economic effects of implementing environmental policy measures.

It needs to be mentioned, however, that pure MRIO models are not accurate and precise enough to calculate Ecological Footprints of individual products; the resolution on the micro level is not high enough [196]. The methodological option for this specific research question is to combine product-specific, bottom-up process analysis with the top-down input-output analysis in a hybrid life cycle analysis (Hybrid-LCA) approach. This is state-of-the-art in LCA, see e.g., [22,197-204]. Such an approach allows preserving the detail and accuracy of bottom-up approaches in lower order stages, while higher-order requirements are covered by the input-output part of the model.

No full, international EF-MRIO model has been empirically tested yet. First steps however have been taken. Wiedmann [36] presents first empirical results of a partial EF-MRIO analysis for energy footprints and [13] use a one-sector EF-MRIO covering 239 countries for their dynamic EF model (see below). Also, a project funded by the European Commission has started in 2009, aimed at integrating ecological, water and carbon footprint accounts with a multi-region input-output model (http://www.oneplaneteconomynetwork.org).

Uncertainty analyses IOA-based calculations have been presented for the carbon footprint in a MRIO framework [196] and the Ecological Footprint of a nation in a SRIO framework [205]. Both studies consider the uncertainty of technical coefficients in the underlying IOA framework.

Input-output based models, such as UK-MRIO, are comprehensive, detailed and robust and thus have a high relevance for national and international environmental policy-making. Recent publications have demonstrated the political relevance of consumption-based national greenhouse gas emission inventories based on MRIO models [206,207]. In the Ecological Footprint community, the possibility of using a MRIO approach for the compilation of National Footprint Accounts has entered the discussions stage [208].