Uncertainty in Ecological Footprint standard method accounts

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Dissertation submitted in partial fulfilment of a
Philosophiae Doctor degree in Environmental studies

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Abstract

The call for a sustainable development of human societies is becoming ever louder. The term sustainability has as a result become thoroughly incorporated into everyday speech, not least among politicians. For the term to hold any meaning some quantitative definitions are needed. We need to know what is sustainable and what isn't. This is where sustainability gets complicated. Being able to clearly define what is sustainable and what isn't is notoriously difficult – not least in a world with very complex globalized trade systems. To tackle this problem the UN called for the creation of sustainability indicators in the early nineties. These indicators were supposed to give an indication of what is sustainable and what isn't and thus aid us in creating the much-coveted sustainable world. In the following years many such indicators were created – among them the Ecological Footprint (EF). EF has been called by some academics "*extremely successful*" but has at the same time had its fair share of criticism. The aim of this dissertation was to examine EF from the standpoint of uncertainty in input parameters. To do this a single case study method was utilized by focusing on the extreme case of Iceland – an outlier in Ecological Footprint accounts under the defined standard method. The most sensitive areas for the case were identified as the Marine and Carbon footprints, and a deep dive performed on each of the two areas. The work was published in three separate academic papers appearing in peer reviewed academic journals. The results indicate that major uncertainties are involved in EF accounting under the standard method. Their sources are identified as uncertainty in input data, lack of knowledge of natural systems and aggregation and use of averages. Six mitigation measures are suggested to meet these challenges. Regardless, this uncertainty makes the EF vulnerable to abuse and misleading information and it is therefore imperative to always give clear indications of uncertainty levels when publishing such results. Under such conditions science can quickly become tainted and thus great care must be taken not to mix scientific endeavours with political agendas or activism of any kind.

Útdráttur

Krafan um sjálfbæra þróun verður stöðugt háværari. Ein afleiðing þess er að hugtakið sjálfbærni er nú orðið hluti af daglegu máli, ekki síst meðal stjórnmálamanna. Til þess að hugtakið hafi einhverja raunverulega merkingu þurfum við mælanlegar skilgreiningar á því. Við þurfum að vita hvað er sjálfbært og hvað ekki. Það er einmitt þá sem sjálfbærnin fer að flækjast. Að skilgreina með afgerandi hætti hvað er sjálfbært og hvað ekki er nánast ómögulegt – ekki síst í heimi stórtækra, hnattrænna viðskipta. Snemma á tíunda áratug síðustu aldar kallaði UNCED eftir sjálfbærnivísum (e. sustainability indicators) til að takast á við þennan vanda. Vísunum var ætlað að gefa vísbendingar um hvað væri sjálfbært og hvað ekki og hjálpa þannig við að skapa hinn langþráða sjálfbæra heim. Í kjölfarið var mikill fjöldi slíkra vísa hannaður og þar á meðal vísir sem nefndist Vistspor (e. Ecological Footprint). Vistsporið hefur notið „*fádæma velgengni*“ (e. extreme success) að mati sumra fræðimanna en hefur jafnframt fengið á sig harða gagnrýni. Markmið þessarar rannsóknar var að leggja mat á vísinn út frá óvissuþáttum í inntaksbreytum (e. input parameters). Ísland var notað sem sérstætt tilvik fyrir rannsóknina en landið er frávik í Vistsporsmælingum vegna gríðarstórs Vistspors. Þættirnir sem innihéldu mestu óvissuna voru sjávarspor og kolefnisspor og var nánar kafað ofaní þessa þætti. Niðurstöður rannsóknarinnar birtust í þremur greinum í ritrýndum vísindatímaritum. Niðurstöðurnar benda til talsverðar óvissu í Vistsporsmælingum og má rekja ástæður hennar til grunninntaksgagna, skorts á þekkingu á ýmsum náttúrulegum ferlum ásamt samþjöppun og meðaltalsnotkun. Sex leiðir til að vega á móti þessum vandamálum voru lagðar til. Umrædd óvissa gerir það að verkum að Vistsporið er útsett fyrir misnotkun og misvísandi skilaboðum og þess vegna er nauðsynlegt að gera skýra grein fyrir óvissunni þegar slíkar niðurstöður eru kynntar. Við aðstæður sem þessar geta vísindin auðveldlega gruggast og því er mikilvægt að halda vísindunum algjörlega óháðum pólitík eða aktivisma af nokkru tagi.

To
SM

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Abbreviations

EF	Ecological Footprint
CF	Carbon footprint (as defined by EF)
MF	Marine footprint
GFN	Global Footprint Network
NFA	National Footprint Accounts
SM	Standard method
MRIO	Multi-region input-output analysis
IO	Input-output analysis
CLUM	Consumption land use matrix
COICOP	Classification of individual consumption by purpose
P	Production (under CF – CO2 emissions)
OSFr	Ocean sequestration fraction rate
AFCS	Average forest carbon dioxide sequestration
EQF	Equivalence factor
IPCC	Intergovernmental panel on climate change
DR	Discount rate
TL	Trophic level
TE	Transfer efficiency
EXTR	Extraction rates
NPP	Net primary production
PP	Primary production
PPR	Primary production rate
GAEZ	Global Agro-ecological Zones
BC	Biocapacity
gha	Global hectares
YF	Yield factor
IEA	International Energy Agency
UNCED	United Nations Conference on the Environment and Development
SI	Supplementary information
GLs2006	IPCC Guidelines for national greenhouse gas inventories
EA	Icelandic Environment Agency
NEA	National Energy Authority (Iceland)
GHG	Greenhouse gas
NVC	Net calorific value
CC	Carbon content
COF	Carbon oxidation factor
CDIAL	Carbon dioxide information analysis centre
OFAT	One factor at a time
SE	Standard error
WHO	World Health Organization
DoH	Directorate of Health
UNR	Unit for nutrition research

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My gratitude extends to the generations that have gone before me and built a society where I am afforded the possibility of a higher education. I further thank the University of Iceland, the Doctoral Grants of the University of Iceland, NordForsk (GreenMAR) and my excellent dissertation committee Dr. Jukka T. Heinonen, Dr. Brynhildur Davíðsdóttir and Dr. Eeva-Sofia Säynäjoki for all their wisdom and advice.

Terminology

This dissertation aims at using generally accepted terms to avoid confusion and misunderstanding. All the same, some generic terms are used repeatedly and need clarification:

Research/work/thesis/dissertation
The words “work”, “research”, “thesis” and “dissertation” are used interchangeably throughout, and all refer to the project as a whole – the dissertation in its entirety.

Study/studies/papers
The thesis is built around three individual but interconnected articles, published in peer reviewed scientific journals. These articles are generally referred to as “the studies” or “papers”.

List of publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals. Thesis author is responsible for initiating, executing and writing the papers. Co-authors provided advice, comments and suggestions.

Paper I
JÓHANNESSON, S. E., DAVÍÐSDÓTTIR, B. & HEINONEN, J. T. 2018. Standard Ecological Footprint Method for Small, Highly Specialized Economies. *Ecological Economics,* 146**,** pp. 370-380.

Paper II
JÓHANNESSON, S. E., HEINONEN, J. T. & DAVÍÐSDÓTTIR, B. 2019. Increasing the accuracy of marine footprint calculations. *Ecological Indicators,* 99**,** pp. 153-158.

Paper III
JÓHANNESSON, S. E., HEINONEN, J. & DAVÍÐSDÓTTIR, B. 2020. Data accuracy in Ecological Footprint's carbon footprint. *Ecological Indicators,* 111**,** 105983

1 Introduction

Humans live in and of nature. We thus affect – and are affected by - nature. This vital relationship has often confounded and confused us, as can be seen in the multitude of examples of civilizations collapsing under the weight of their own overutilization of natural resources (Diamond, 2005). This has led us to understand that there are limits to how much of the natural resources we can use before the natural systems we are utilizing are permanently changed (Meadows et al, 1972; Barnosky et al, 2013). In response, a variety of indicators – sometimes referred to as environmental-, ecological- or sustainability indicators - have been created in an attempt to identify the signs that show that we are endangering the natural world with our actions – in order for us to take the necessary actions to rectify the matter (Cobb and Cobb 1994; Wackernagel and Rees, 1998; Lawn and Sanders 1999; Hanley, 2000). Indicators are therefore closely linked to policy (Heink and Kowarik, 2010). The link to policy gives indicators in the environmental sphere further importance. This importance in turn underlines the necessity of mitigating uncertainty involved in such measurements. Think of engineers with incorrect rulers and the damage they could do. Similarly, environmental scientists trusting the results of an indicator – without knowing the uncertainty involved - are not only ill informed but can be downright dangerous – depending on how much impact they are having on policy – or even public perception.

Humans have likely been looking to indications from nature to inform their behaviour since the earliest of times as suggested by Rapport, 1992. The earliest recorded remark on environmental indicators Rapport, 1992 suggests might be attributed to Plato. The field is often confusing with very many suggested indicators, taking a variety of standpoints and approaches to the problem - or problems – depending on their stated purpose and scope. To add to the complexity, Heink and Kowaric, 2010 find there is ambiguity regarding the term "indicator" as used at the interface between science and policy, and a need for a clear definition. In the first of the three scientific articles of this thesis a few definitions of the term are given. All of those stress the need for an indicator to be simple and/or understandable. Simplifying complex matters on the other hand may not be as simple as it sounds. In the words of Slobodkin, 1994 (p.76):

> *"Any simplification limits our capacity to draw conclusions, but this is by no means unique to ecology. Essentially, all science is the study of either very small bits of reality or simplified surrogates for complex whole systems. How we simplify can be critical. Careless simplification leads to misleading simplistic conclusions."*

Stephen Morse co-author of *Measuring the Immeasurable* attempted to do this very thing when asked what indicators are, by answering:

> *"Indicators are a way of trying to represent something complex in something simple…" (The OpenLearn team, 2010)*

One sustainability indicator that seems, on the surface at least, simple enough, is the Ecological Footprint (EF). EF is a very successful indicator in terms of popularity and use (Binningsbo, 2007; Blomquist et al, 2013; Syrovátka, 2020) and this success is arguably down to its simplicity – not in its methodology but rather in its dissemination of results. Blomquist et al, 2013 (p.1), describe how…: *"EF has influenced the policies and communications of many governmental and non-governmental organizations…"* and list how it is used in such wide ranging settings as World Wildlife Fund's Living Planet Report, Worldwatch Institute's State of the World, the Global Environment Outlook of the United Nations Environment Program, the United Nations Development Program's Human Development Report, and the International Union for Conservation of Nature (IUCN)'s Transition to Sustainability; the Convention on Biological Diversity. The influence of these institutions is hard to contest – on policy makers, the media and public opinion. EF is thus influential and therefore important. It is this importance that guides the purpose of this thesis.

EF was first introduced in 1992 by William Rees, 1992 and further developed by Rees and his then student Mathis Wackernagel in the following years (Wackernagel and Rees, 1997; Wackernagel and Rees, 1998). In 2003 Wackernagel founded an NGO named the Global Footprint Network (GFN), with his partner Susan Burns. According to the organization's website the core of their work evolves around EF (footprintnetwork.org). Every year GFN publishes their annual National Footprint Accounts (NFA), which now cover over 200 countries. NFA use international databanks to calculate the EF for every country included in the accounts, according to the *standard method* – a standardized version of the methodology of EF accounting, upheld by the GFN in order to aid comparability and diffuse confusion. The influence and reach of EF have been considerable and have some academics described it as: "*The extraordinary success enjoyed by the Ecological Footprint…*" (Giampietro and Saltelli, 2014a, p.620). According to Giampietro and Saltelli's analysis this success has been achieved by EF's proponents having…:

> *"… successfully filled a gap in the market by designing a straightforward numerical indicator whose simplicity appeals to the media and general public and whose mild verdict has found ready approval with the political establishment.*" (Giampietro and Saltelli, 2014a, p.610).

The GFN website (GFN, 2020) lists their outreach accomplishments as:

- Inclusion of NFA results in countless reports by organizations like the World-Wide Fund for Nature (WWF), the International Union for Conservation of Nature (IUCN), UN Environment, and the European Environment Agency
- Engagement with more than 70 governments on six continents
- Partnership with over 80 organizations
- The EF being used by 15 national governments to inform their policy initiatives
- 17 million visitors to their online EF calculator
- 4 million media impressions in over 120 countries, this year, about the Earth Overshot campaign

The website further states:

> "*Over the years, the Ecological Footprint concept has grown to become a household phrase around the world. The term "footprint" has become synonymous with human behavior and its impact.*" (GFN, 2020)

If EF can claim sole responsibility for the use of the term footprint in ecological circles is debatable but there seems little doubt about the influence of EF on – not only environmental literature – but the public and policy makers too.

"*The extraordinary success enjoyed by the Ecological Footprint…*" (Giampietro & Saltelli, 2014a, p.620) has not come without criticism. Notable critical analysis include Gordon and Richardson, 1998; van den Bergh and Verbruggen, 1999: VROMraad, 1999: Ayres, 2000; Moffatt, 2000; Opschoor, 2000; van Kooten and Bulte, 2000; EAI, 2002; Grazi et al., 2007; Lenzen et al., 2007; Fiala, 2008; van den Bergh and Grazi, 2010; Blomqvist et al., 2013a and Blomqvist et al., 2013b; van den Bergh and Grazi, 2014a and b; Giampietro & Saltelli, 2014a and b; van den Bergh and Grazi, 2015, with most critics focusing on technical aspects of the methodology and the method's underlying assumptions. Issues with data quality and uncertainty related to input parameters has not received as much attention with the exceptions of Parker and Tyedmers, 2012; Kitzes et al, 2009; Giljum et al, 2007 and Schaefer et al, 2006, who all highlighted the importance of those issues.

No data analysis, such as called for by Kitzes et al, 2009, Giljum et al, 2007 and Schaefer et al, 2006 can be found in the literature more than a decade after these publications. The work presented in this thesis is an initial attempt towards such analysis.

Considering how widespread and influential EF is, it is imperative to have an idea of the uncertainty involved with the results – the indications. The work presented here followed on the work of Jóhannesson, 2010, which showed Iceland as a complete outlier in EF measurements in terms of the size of the footprint. The reasons for this were unclear and needed further exploration. That was the starting point of this research. The research focal point then moved with the results to what was highlighted as the most sensitive areas. Iceland was used throughout as a case study and as such functions very well since the findings apply equally to all other cases – although with less extreme cases the uncertainty can get lost in more evenly balanced accounts. In short, the extremes of Iceland help highlight issues that otherwise may go unnoticed. The work evolved around uncertainty in some important input parameters, mainly data and key constants and thus the research question became:

What can Iceland, as an outlier in EF standard method accounts, teach us about the uncertainty involved with the calculations?

The thesis consists of three papers - which all have been published in peer reviewed scientific journals – and a compilation part. In the papers specific research questions were asked to move the inquiry further forward towards answering the overall research question above. The questions the papers ask are:

Paper I
How well does EF standard method handle a small, highly specialized economy and what are the main sources of bias?

Paper II
What are the main sources of bias within the marine footprint component of EF and how can it be mitigated?

Paper III
What is the uncertainty involved with carbon footprint calculations in regard to the production variable?

The focus of the work presented here is thus on the data used for the accounts, mainly input data but with concern for other factors that influence the results, such as key constants – as they are presented in the Global Footprint Network's National Footprint Accounts, under their standard method. The compilation part attempts to answer the main research question, taking into account the questions raised and answered by the individual papers, which were all published in academic journals between the years 2018 and 2020. The three articles analyse the data used for the Global Footprint Network's NFA's, using Iceland as a case study. The first article looks at the whole of the accounts while the second and third dive into what the first article highlights as the most sensitive areas, the marine footprint (MF) and the carbon footprint (CF), respectively. The footprint is re-calculated using local data and sensitivity tests are made. The overarching argument arising from the results is that uncertainty levels are a concern in EF standard method calculations as currently performed. Several causes of uncertainty are identified: Use of international databases which prove lacking in accuracy when compared with local data, use of estimates in the face of lack of knowledge of natural systems and processes, use of averages where exact data collection becomes too cumbersome, bias arising from aggregation for ease of calculation, data gaps where no data can be found and inaccuracy arising from simplification of the accounts.

This thesis agrees with – and continues the work of - Parker and Tyedmers, 2012; Kitzes et al, 2009; Giljum et al, 2007 and Schaefer et al, 2006, all of which put data quality issues at the forefront of the imminent research needed for furthering the EF accounts. Parker and Tyedmers, 2012, conclude that imprecision in the calculations is due to uncertainty in input data and although their paper is focused on the marine footprint, this arguably holds for the accounts as a whole as indicated by the work presented here.

In 2009, Justin Kitzes along with some of the leading figures in Ecological Footprint accounting published an article entitled: *A research agenda for improving national Ecological Footprint accounts*. As the title suggest the article lays out the most important issues and topics to be studied further with the EF, as well as responding to some of the criticism mentioned here earlier. The twenty-six topics suggested in the article fall into seven categories: Data, Global hectare accounting, Land types, Trade, Energy and carbon, Other major impacts and Application and policy use. It is undoubtedly no accident that data is the first item on the agenda. The EF, like any statistical model, can never be more accurate than individual data sets that it relies on – but can, due to compounding errors, be much more inaccurate than the data it uses. This means that errors in data can magnify under a set of circumstances within the model. In addition to primary input data the authors further highlight the importance of key constants. These constants, such as per hectare CO_2 sequestration of world-average forest (IPCC, 2006; Mancini et al. 2015), total sustainable marine harvest (FAO, 1971; Pauly, 1996) and the feed conversion ratios and feed baskets of livestock (Steinfeld et al, 2006) play a significant role in these sensitive and complex calculations. Kitzes et al (2009) underline this and call for sensitivity analysis of those key constants used under the standard method of EF as well as the primary input data.

In a report for the German Federal Environment Agency, Giljum et al, 2007, in their assessment of EF, pointed out how many examples of errors had been found in the FAO data. Their suggestion was that individual national EF accounts were audited by a partnership of national organizations, who would check the FAO data – and other data from international databanks - against more robust national data – where such data were available. Schaefer et al, 2006, reach similar conclusions and highlight how sensitive the accounts are to issues with data quality. They emphasize the need for high quality data for all input variables and a technique to estimate missing values. They further find that the margin of error in the accounts is difficult to quantify.

Since the publication of Parker and Tyedmers work (2012), no analysis of data issues in EF can be found in the literature. The work presented in this thesis is an initial attempt towards such analysis, including quantification of error margins. The thesis does not provide a comprehensive analysis of the uncertainty involved with EF standard method calculations, but rather shows certain crucial weak spots and discusses amendatory actions for improvement.

In a recent article Reid and Rout, 2020 discuss the need for the uncertainties involved with sustainability indicators in general to be made clear. The results of this thesis support this sentiment. The results further support - in general – those studies that conclude that EF needs further development, such as Kitzes et al, 2009; Bastianoni et al, 2012 and Giempietro and Saltelli, 2014. The academic importance of this thesis lies in showing how much development is still needed for the indicator before it can reach anything nearing acceptable levels of uncertainty as well as highlighting the causes of bias. This also raises questions about any environmental indicator using global databanks for their primary input data. On a policy level the thesis shows the dangers hidden in trusting blindly in results of EF, especially if no clarification of estimation and inaccuracy in data is given alongside those results. Making policy decisions on such uncertain results, where the error margin is as large as the results of the studies of the dissertation show, is ill advised.

The next chapter of the thesis presents the methodology of EF accounting – the standard method – and discusses three important debates that have appeared in the literature in recent years, chapter 3 describes how the thesis was designed, chapter 4 details the results from the papers and the thesis as a whole, chapter 5 discusses the results and puts them into context and chapter 6 closes the compilation part with concluding remarks. Chapter 7 contains the three published papers and their supporting information.

2 The Ecological Footprint Standard Method

This chapter gives a descriptive overview of the Ecological Footprint standard method, as defined by the Global Footprint Network. A more detailed look at the mathematics behind the method can be found in papers I-III. The chapter also includes a “conversation” created from three different debates on the merits of EF that appeared in the literature in the years 2013 – 2015. This conversation, that has been created from these three debates, is included here since, arguably, they have been instrumental in shaping the discourse on EF ever since they appeared. Since their publication two camps have effectively formed between those who favour the method and those who doubt its merit. A middle ground that used to exist between those two factions seems to have all but disappeared in the wake of those debates. It is therefore important to get a sense of what they were about and their conclusions – or lack thereof.

2.1 EF SM, a descriptive overview

The thesis uses the standard method (SM) of EF as defined by GFN as a basis for the work. Many variations of the standard method have appeared in the literature (Lenzen & Murray, 2001; Nguyen & Yamamoto, 2007; Zhang et al, 2020), none of which are under investigation here. The latest version of the GFN standard method is explained in Lin et al., 2018 and Borucke et al., 2013. Further to these papers on the methodology, GFN has created a set of standards they ask practitioners to adhere to when calculating EF. These standards were last published 2009 by GFN in the document *Ecological Footprint Standards 2009* (GFN, 2009). The standards were created to: *“... ensure that Footprint assessments are produced consistently and according to community-proposed best practices*” (GFN, 2009, p.1) with the aim to: *“...ensure that assessments are conducted and communicated in a way that is accurate, transparent, and does not misrepresent the results of the assessment* (GFN, 2009, p.1). The standards lay out what EF calculations should comply with in order to fall under the standard method. The standards further indicate what is considered allowable deviation from the set-out method – such as inclusion of local data or use of multi-regional input-output (MRIO) analysis to assess trade flows. The second standard listed in the document (standard A.2) mandates all standard compliant studies to be consistent with the National Footprint Accounts (aside from allowable unconventional practices listed under standard A.3 – which include using more recent or more accurate data, inclusion of consumption categories currently not included in the NFA’s, using MRIO’s for trade flows etc.) – making the accounts the template for SM compliant EF calculations. The NFA’s use a top-down (compound) method to calculate the EF at the national level. A consumption land use matrix (CLUM) is employed under a process-based method, using the UN’s COICOP categorization system for consumption categories.

The NFA’s are created annually by GFN and since their inception in 2004 have grown to cover over 200 countries. Each country account contains up to 15.000 data points (Lin et al, 2018) and results are displayed in units of global hectares (gha). In order to convert hectares into global hectares, two co-efficients are used: a yield factor (YF) to adjust for difference in yields between the same land types in different countries and an equivalence factor (EQF) to adjust for the difference in the bio-productivity of different land types. In this manner each country gets a yield factor for each land type depending on the ratio between local yields to global yields, while EQF is calculated each year by GFN based on suitability indexes from the Global Agro-Ecological Zones model which are combined with data on the actual areas of cropland, forest land, and grazing land area from FAOSTAT (FAO and IIASA, 2000, FAO, 2012).

Bio-productive areas are divided into six categories: Cropland, grazing land, forests, fisheries, built-up land and carbon uptake land. Human appropriation of these is then estimated via calculations based on trade flows in mass units and via allocation to the relevant land type. Due to the conversion into gha the impacts can then be summed up within and between land types to give a one number figure for each land type and a total figure relaying the EF of the area under investigation. The same method is used for estimating nature’s annual production of usable renewable resources – or what is called biocapacity under SM. The two, EF and biocapacity, can then be compared. If EF is higher than biocapacity the consumption of the population is considered unsustainable. Sustainable if biocapacity is higher than EF.

What sets EF aside from other sustainability indicators is the idea of estimating on the one hand nature’s production of usable goods (usable in an anthropocentric context) and on the other how much humans consume of those goods. The idea is simple and aims to cut to the heart of the issue of environmental impacts of human consumption – how much do we have and how much can we spend. Simple accounting. Unfortunately, the estimations both on the production and the consumption side quickly become quite complex – arbitrary some say, such as in the case of carbon footprints (van den Bergh and Grazi, 2013; Giampietro and Saltelli, 2014) - due to a lack of knowledge of various natural processes and, not least, a lack of necessary data for the execution. This complexity has led to some serious criticism of EF, its method and basic assumptions.

2.2 Critique and defence of EF

Although an overwhelming majority of studies featuring EF are favourable to the method – or at least uncritical - a few researchers have been particularly harsh on EF and its alleged shortcomings. The proponents of EF, mainly associated with GFN, have responded to some of these critical reviews leading to three separate published scientific debates – all taking place in the years 2013 - 2015. These opposing parties have effectively formed two camps in the EF literature – yet, as stated before, with majority of users utilizing the method without much critical review. Arguably, these debates have been instrumental in shaping the general opinion of EF in recent years, not least within academic circles. It is therefore important to get a sense of the back-and-forth comments and replies – what questions were being asked? How were they answered? And what were the results?

The first debate, one between van den Bergh and Grazi on the one hand and Wackernagel, Lin and other GFN associates on the other, took place in 2013, 2014 and 2015. van den Bergh and Grazi, 2013 built on their earlier article from 2010 as well as on van den Bergh and Verbruggen from 1999. van den Bergh and Grazi, 2013 detail their criticism in eight points as well as commenting on the policy relevance of the EF[1]. Wackernagel, 2014 does not respond directly to these eight points but directs readers to earlier articles where these questions have supposedly been answered. Some of these answers are included here. This led to a reply by van den Bergh and Grazi, 2014 and a counter by Lin et al., 2015, which van den Bergh and Grazi, 2015 reply to.

The other two debates are shorter, only spanning three articles each, but no less vigorous. Two articles by Blomqvist et al. appeared in 2013, with a response to the first one by Rees and Wackernagel, 2013 and in 2014 Giampietro and Saltelli published two articles with a response to the first one by Goldfinger et al., 2014. A follow up study was a joint effort between the parties – i.e., Giampietro and Saltelli on the one hand and EF proponents on the other - where they each chose 5 questions that both parties then answered (Galli et al, 2016). This follow up study is not included in this overview since it is in itself an overview, although approaching the debated issues from a slightly different angle in pre-setting the questions and thus further highlighting the differences in opinions.

In the following section quotes from these debates have been edited together to give a sense of the opposing opinions and the liveliness of the debate. Of the many issues raised in these debates only a few are highlighted here as the most relevant for this thesis and further development of EF. These issues fall under six headings:

- Issues with CF
- No overshoot without CF
- Exclusion of environmental pressures
- Hypothetical nature of EF
- Failure to declare uncertainty levels
- Aggregation issues

In spite of these fierce debates, no agreement has been reached on any of them. As stated above, two camps have been formed with neither camp seeming any closer to seeing the other's point. The following excerpts are thus here mainly to illustrate what has taken place in the debates without any resolution. Chapter 5 will then detail how, according to the findings of this thesis, these issues might, at least in part, be dealt with.

2.2.1 Issues with CF

The three groups of critics in these debates all find major flaws with CF accounting under EF. They doubt the assumptions behind the method, the method of choice to sequester CO_2 and the uncertainty of the data. van den Bergh and Grazi, 2013 (p.13), maintain that including CO_2 emissions and leaving out many other kinds of impacts, is arbitrary:

> *"Just because CO_2 emissions contributing to climate change can be connected to carbon sink lands and thus land use—as opposed to, for*

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[1] The name of their 2010 study was *On the policy relevance of the Ecological Footprint*

> *instance, acid rain or ozone depletion, which cannot be so easily tied to land use—does not mean that one should use this connection to translate CO_2 in land use and omit acid rain and ozone depletion from the equation."*

Mathis Wackernagel, 2014 does not reply directly to this or the eight points of criticism levied at EF by van den Bergh and Grazi, 2013 but claims these points have all been made before and answered. In that respect one of the sources he mentions holding answers is Wackernagel and Silversteen, 2000 (p.392):

> *"The only ecosystems that can remove significant amounts of CO_2 from the atmosphere, at least for their first 30 – 50 years, are growing forests — and using them to sequester CO_2 is still the prevailing technology."*

van den Bergh and Grazi, 2014 (p.23):

> *"But, our point simply is that carbon sequestration can be realized in many other ways, on land and in the oceans. Focusing on carbon sequestration through forestation is hypothetical and arbitrary..."*

This debate continues in the follow up articles by van den Bergh and Grazi, 2015 and Lin et al, 2015 without resolution.

Blomqvist et al's 2013 (p.2) comments on CF were brief and to the point:

> *"... humanity's global EF is practically equivalent to its carbon footprint..."*

Rees and Wackernagel, 2013, point out that this is not strictly correct – although their inverted commas around the word "just" in the following quote, indicate that they realize the absurdity of using the word for one of six land type categories being responsible for over half the global footprint:

> *"This is incorrect. The carbon Footprint is only a small fraction of the domestic Footprints of many countries... CF is "just" 55% of global EF in 2008."*

Blomqvist et al, 2013 (p.3) also raise an important point about the accuracy of the carbon sequestration rates used in EF calculations, the so-called average forest carbon sequestration rate (AFCS):

> *"The large natural variability in carbon sequestration rates over time and space – and major uncertainties in their measurements- makes this extreme sensitivity a reason for caution."*

Rees and Wackernagel, 2013 (p.2):

> *"... our carbon Footprint is based on current best estimates of de facto average sequestration rates..."*

Blomqvist et al, 2013 (p.3):

> *"The net uptake of carbon in terrestrial ecosystems has, over the past 5 decades, fluctuated between zero in some years to nearly 6 Gt C yr^{-1} in others."*

Rees and Wackernagel, 2013 (p.2):

> *"We ... have acceptable estimates of sequestration rates by average forest ecosystems based on an extensive literature review, on Food and Agriculture Organization and Intergovernmental Panel on Climate Change reports..."*

Following this exchange, Mancini et al, 2016, revisited the work on CF and the all-important average forest carbon sequestration rate. The AFCS they set at 0.73 t C ha^{-1} yr^{-1}, with a standard error of ± 0.37 t C ha^{-1} yr^{-1}. Paper III of this thesis shows the impact this 50% standard error has on the uncertainty level of the accounts.

This thesis finds CF accounting riddled with uncertainty and suggests dropping CF from EF accounts on these grounds. This would effectively resolve all the issues above as well as make the accounts purely focused on resource depletion, with no accounting of pollution sinks. This issue will be further discussed in chapter 5 below.

2.2.2 No overshoot without CF

The next issue is closely related to CF since it deals with how, if CF is taken out of the equation, the remaining land types show little change since 1960 - the time span covered by the NFAs – and are, together, only responsible for roughly half of global EF, against CF's other half. Blomqvist et al, 2013 (p.1), explain this succinctly:

> *"When the global EF is decomposed into its six components, none of the five non-carbon land-use categories has any substantial ecological deficit—suggesting that depletion of cropland, grazing land, forest land, fishing grounds, and built-up land is not occurring on an aggregate, global level... if one excludes carbon, global biocapacity exceeds the footprint of consumption by about 45% in 2008."*

Rees and Wackernagel, 2013 (p.2) respond by pointing out that if it wasn't for lack of better data the land categories of forests, cropland and fisheries would not show sustainable utilization and global EF should be larger:

> *"... current cropland, forest land, and marine Footprints do not, in fact, reflect depletion but this does not imply that there is none. ... However, to make reliable adjustments would require globally consistent data sets, which do not exist."*

This sentiment is supported by this thesis and paper II suggests that using case specific, local data may correct the accounts to the point where they would not indicate that the world's oceans were being utilized sustainably as is currently the case.

Giampietro and Saltelli, 2014 (p.613) draw attention to the fact that the five categories – excluding CF – have actually changed very little for the global accounts over the 45 years they had been calculated at the time of their paper:

> *"Yet, according to the Ecological Footprint analysis... apart from the CO_2 emission increasingly overshooting the absorption capacity, nothing much happened over the past 45 years in relation to the non-energy-related ecological footprint. Hence, we are left to conclude that according to this assessment over the past 45 years the carrying capacity of this planet steadily rose, since the increase in the consumption of food and biomass did not cause any harm to the natural capital of our planet."*

Goldfinger et al, 2014 (p.628) reply that this is because the increased productivity of the five categories other than CF has been reached through more use of oil and therefore the increased footprint ends up under CF:

> *"Giampietro and Saltelli correctly point out... at the global level the carbon Footprint increased rapidly over this period, while the sum of non-carbon components has increased little if at all... This is consistent with the observation that the rapid growth of agricultural productivity has been enabled largely by fossil fuel-based inputs (Lotze-Campen et al., 2010; Tilman, 1999; Woods et al., 2010)."*

This thesis suggests that correction of data and other important input parameters may result in major changes to the footprint of all categories.

2.2.3 Exclusion of important environmental pressures

Exclusion of important environmental pressures also relates to CF, since CF is the only waste stream incorporated into the accounts and this issue is to a large extent about waste streams that are not included. This will be discussed further later in the thesis. The proponents of EF give various reasons for why so many waste streams are excluded; insufficient data (Wackernagel and Silversteen, 2000), EF was never intended to be a complete measure of sustainability (Goldfinger, 2014) and only pollutants that can be measured by areas of land are included (Lin et al, 2015) as we can see in the highlights below.

van den Bergh and Grazi, 2013 (p.13):

> *"... water pollution, emissions of toxic substances (including heavy metals), noise pollution, depletion of the ozone layer, acid rain, fragmentation of ecosystems resulting from land use and road*

> *infrastructure, and, more generally, biodiversity are not accounted for by the EF approach."*

The first explanation for this is from Wackernagel and Silversteen, 2000 (p.393):

> *"…leaving out freshwater consumption and an array of waste streams, due to insufficient data, further underestimates footprints."*

Lin et al, 2015 (p.466) give a different answer:

> *"…because of the methodology's underlying assumptions (see Wackernagel et al., 2002), only those resources, pollutants or services that can be measured in terms of biologically productive surfaces are included in the Ecological Footprint."*

van den Bergh and Grazi, 2015 (p.460), don't seem too satisfied with this reason given by Lin et al, 2015:

> *"… global warming, a pollution and not resource extraction issue, is completely integrated in the footprint method through the scenario of the carbon sequestration by forestation. However, other pollution problems are absent, not because they are irrelevant, but as there is not obvious way to translate them into hectares."*

Giampietro and Saltelli, 2014 (p.619), take a different approach to the issue, which they claim to be a result of the aggregation of EF into single number results:

> *"The EF approach cannot handle the complexity of sustainability because of its goal to deliver a simple narrative (a single number addressing all dimensions of sustainability)."*

Which leads Goldfinger et al, 2014 (p.624), to give yet another explanation:

> *"They are quite correct in pointing out that Footprint accounting cannot, on its own, "handle the complexity of sustainability," for it was never intended to do so.*"

They go on to explain how EF measures an aspect of sustainability – not all aspects of it.

All three reasons given by EF proponents are true; there are no data available for a variety of issues but if there were, it would likely be impossible to include those in the accounts unless their impact could, somehow, be converted into land use and lastly, EF can't – no more than any other indicator – cover all aspects of sustainability – regardless of if this was the original intention or not by EF's creators. As pointed out later in this thesis, dropping CF from the accounts would make the EF only a resource use indicator and would completely leave out all pollution, making the indicator internally coherent and clearly defined. This would effectively end this debate.

2.2.4 Hypothetical nature of EF

Chapter 5 discusses (among other things) the question: Is metaphor a valid scientific construct? This question seems to be underlying many of the following concerns about the hypothetical nature of EF. CF plays a role here too as that is one area highlighted as involving hypothetical situations. The issue was raised by van den Bergh and Verbruggen (1999) and again in van den Bergh and Grazi (2010). Wackernagel et al. responded in 2004 (p.277), by saying:

> *"'Hypothetical'' is a misleading qualifier... The biosphere's sequestration capacity can theoretically be translated into biologically productive hectares, in much the same way resource managers determine sustainable yields of forests and fisheries."*

Still, in their critical analysis, van den Bergh and Grazi, 2013 (p.12) include the issue again:

> *"The EF converts flows of energy and matter to and from economic activities in hypothetical land area (in ha or square kilometers [km^2]) that would be needed to sustain these flows. Yet, the possibility exists that this is interpreted as realistic or, worse even, actual land area."*

Wackernagel, 2014 (p.20), further explains his point:

> *"This approach parallels financial statistics that convert different currencies into (nominal or constant) U.S. dollars, farmers who adjust calculations of available land for its ability to support cattle (expressed as "cow-calf acres" or "animal units" in rangeland management), or various types of greenhouse gases (GHGs) that are converted into carbon dioxide (CO2) equivalents for their equivalent warming potential. In footprint accounts, the common denominator is units of biocapacity expressed in gha."*

van den Bergh and Grazi, 2014 (p.23) respond by using Wackernagel's own words against him:

> *"Wackernagel says further, "For instance, nowhere do footprint accounts measure hypothetical hectares (ha). They are real areas. Real demand is compared to real supply." We are surprised by this statement, because, in our view, it misrepresents how the EF method works. Indeed, on the demand side, energy land is a very clear illustration of hypothetical land (because carbon emissions are translated into forest land); and, on the supply side, global ha (gha; ha with world average productivity) are not concrete ha of land, but are corrected for productivity differences. So, footprint accounts do report hypothetical, and not real, ha."*

The debate continues between van den Bergh and Grazi and Lin et al, 2015, with the latter conceding to the former's point that in some GFN literature references have been made to EF measuring real areas and thus adding to the confusion regarding this point. van den Bergh and Grazi, 2015 (p.459), don't seem to accept the explanations and conclude with:

> *"…mixing productivity and area size is confusing and just makes the entire footprint unclear, difficult to understand and easy to misinterpret."*

Blomqvist et al, 2013, do not comment on this issue but Giampietro and Saltelli, 2014 do, with Goldfinger et al, 2014, responding in a similar way to their colleagues before them and the issue is left just as unresolved as in the previous debates. As illustrated in chapter 5 below, this thesis argues that using metaphor is a valid and useful construct in ecological economics – and is, arguably, a key factor in EF's *"…extraordinary success…"* (Giampietro & Saltelli, 2014a, p.620).

2.2.5 Failure to declare uncertainty levels

Failure to declare uncertainty levels is a problem raised in all three debates. Again, the issue relates to CF since this thesis finds CF to be a part of the accounts where uncertainty is particularly troublesome.

van den Bergh and Grazi, 2015 (p.460):

> *"… if Wackernagel/GFN really think that the footprint is a very incomplete indicator of environmental impacts, than (sic) it would be good to state this clearly in all footprint publications and advertising material, because most innocent users really interpret "footprint overshooting" as a good proxy of overall unsustainability."*

Blomqvist et al, 2013 (p.3):

> *"Humanity's total footprint, as calculated in the EF, is critically dependent on a single, empirically derived variable—the carbon sequestration rate—the estimation of which is highly uncertain…"*
>
> *"Using a single figure without an associated confidence interval gives a false impression of precision and is therefore misleading."*

Giampietro and Saltelli, 2014 (p.616):

> *"Although it is extremely hard, if not impossible, to put reliable numbers into this equation[2] – especially the assessment of Socean[3] is everything but easy (McKinley et al., 2011; Wanninkhof et al., 2012) – the GFN*

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[2] For CF calculations

[3] The fraction of anthropogenic emission captured by oceans in a given year

> *issues no warning that the implementation of this equation may be very problematic."*
>
> *"Any sensitivity analysis would reveal the volatility of the inference, thereby making the EF vulnerable to the critique of Pseudo-Science as defined by Funtowicz and Ravetz (1990, 1994) when discussing quality criteria for science used in support to policy: "[pseudo-science is] where uncertainties in inputs must be suppressed lest outputs become indeterminate." (p.619)*
>
> *"The spurious accuracy of August 22 (as distinct from August 21 or 23) gives the 'viewers' a false sense of security about how accurately the experts can measure the damage…" (p.620)*

GFN's relative silence on this issue, uncomfortably, speaks volumes. This thesis underlines the importance of all EF results to be clearly caveated regarding the uncertainty involved in the accounts. The same applies to all sustainability metrics.

2.2.6 Aggregation issues

Aggregation issues are always problematic in composite indicators and in EF it is not least CF that critics find a fault with, in this respect.

van den Bergh and Grazi, 2013 (p.13):

> *"Another problem is the aggregation of distinct environmental problems by the EF approach. This works by way of implicit weights that are arbitrary and fixed."*
>
> *"For example, 1 km2 of road infrastructure does not have the same environmental impact as CO2 emissions captured by 1 km2 of forest, but they are nevertheless treated as identical."*
>
> *"…This represents a very arbitrary, unscientific approach to accounting for environmental problems and introduces implicit weights of environmental subproblems that do not necessarily make sense from a value or welfare angle. If some problems cannot be transformed to the same denominator, any effort to aggregate them simply will result in pseudoscience."*

These sentiments are shared by Blomqvist et al, 2013 and Giampietro and Saltelli, 2014 but certainly not by Wackernagel and Silversteen, 2000 (p.392), as reflected in the following statement:

> *"We believe that the ecological footprint is robust for two reasons. First, its utilitarian resource accounting is consistent with basic thermodynamic principles, thereby avoiding arbitrary weighting. In other*

> *words it does not require a leap to post-normal science, but makes its point within a positivist (if not mechanistic) framework."*

A formal reply comes from Lin et al, 2015 (p.466):

> *"Weights" are not arbitrary, but are determined according to an activity's relative demand on biocapacity, or an area's relative productivity.*

van den Bergh and Grazi, 2015 (p.461), once again, are not satisfied by the response…:

> *"The use of motivated weights for productivity or demands does not guarantee correct (implicit) weights for distinct environmental problems…"*

…but offer a consolation of sorts (p.463):

> *"Perhaps it is of consolation to footprint devotees to know that other efforts to arrive at an aggregate environmental indicator have failed as well (see the wide range of indicators assessed by Pillarisetti and van den Bergh, 2010, 2013)."*

This thesis recommends dis-aggregation of results for scientific or policy purposes, leaving aggregate results to be used for outreach purposes and education only.

2.3 The "no concensus" concensus

These three academic debates largely capture the criticism of EF up to the year 2015. Since then, no systematic criticism can be found in the literature but in a recent article Syrovátka, 2020 argues for a new way of interpreting EF results and calls for a broader view than the *"…nation self-sufficient and consumption centred perspectives*". Syrovátka points out how the GFN interpretation of EF holds nation states accountable for their consumption but misses out on laying any responsibility at their feet regarding protection of the natural resources within their borders. By focusing on the interpretation rather than the methodology Syrovátka brings a fresh look to some of the subjects dealt with in the aforementioned debates (some of which are not included in the review above) such as aggregation, self-sufficiency and political borders. Syrovátka's approach opens up a new line of discussion within EF circles and as such holds promise for new development in EF accounting.

As can be seen in the highlights above – and even more so in the article following these debates co-written by critics and proponents (Galli et al, 2016) – very little consensus is being reached. The two camps remain steadfast in their views and seem solidified, with the proponents generally feeling EF is misunderstood by the critics or that they want it to be something it isn't rather than accepting it as is - and the critics feeling the proponents and GFN are just digging their heals in and avoiding or disregarding any criticism.

Through a study of the Icelandic case, this thesis offers suggestions regarding the issues dealt with in these debates as mentioned at the end of each of the six topics the chapter deals with. These issues, and how they relate to the results of this thesis, will be considered further in chapter 5 below .

3 Thesis design

In this chapter research methods used for the thesis as well as data collection approaches and methods are described.

3.1 Research methods

The project's starting point was questions regarding the accuracy of EF that arose from the 2010 measurement of the Icelandic EF (Jóhannesson, 2010). Allowing questions and research focus to develop organically the thesis follows these trails to the most sensitive areas identified, mainly MF and CF. The case of Iceland was used throughout as it provided a rich ground for study because of the extremes in bias caused by inaccuracies and errors in data. The core of the study evolved around thorough analysis of results in search for errors and then tracing those to their sources. A wide range of local data was then used to test for sensitivity and attempt to quantify the magnitude of errors in order to make suggestions for improvements.

3.1.1 Use of the single case study method

The 2010 Jóhannesson study indicated that, either there were serious issues with EF's standard method measurements or Icelanders were, by far, the world's largest per capita consumers of natural resources. Iceland's footprint, as calculated according to the standard EF method, was five times larger than any other country's EF in that year. From these findings it was deducted that a thorough study of the Icelandic case might show up issues with the method and/or calculations that were for some reason not showing up with other countries. The single case study method was used to make this exploration in paper I of this thesis. The single case study method was a very suitable fit for the project since Iceland was a clear "extreme" case as defined by Flyvbjerg, 2006. The exploration in paper I then further confirmed the validity of the single case method for the remainder of the research in papers II and III, since it showed how the Icelandic case was not only an extreme case but a critical one as well – but a critical case is a case where the lesson learned from the case under study are general in nature and therefore apply to all other cases too (Flyvbjerg, 2006).

The case study method has been defined and described in the literature (Yin, 1981; Yin, 1984; Miles & Huberman, 1984; Gersick, 1988; Harris & Sutton, 1986; Eisenhardt & Bourgeois, 1988) although variations exist, and a full consensus has not been reached on methodology and implementation. According to Yin, 2014 a case study can be defined as: *"…an empirical inquiry that investigates a contemporary phenomenon (the 'case') in depth and within its real-world context*" (p. 16). A case study is thus intended to dive deep into a single case and capture its complexity. The methodology has been developed mainly within social sciences but is now common practice within other fields including environmental studies (Johansson, 2003).

Dul and Hak's, 2008 definition of case studies, where:

- One case (single case study) or small number of cases (comparative case study) in their real-life context are selected and
- Scores obtained from these cases are analyzed in a quantitative manner

applies to this thesis. The methodology used is in line with Eisenhardt's,1989 roadmap for building theories from case study research. Building on the works of Miles and Huberman, 1984; Yin, 1981, 1984 and Glaser & Strauss, 1967, Eisenhardt, 1989 suggests a method of designing and implementing case study research.

The research question had not been defined at the beginning of this work, but the focus was clear. The aim was to attempt to figure out the reasons for the incredible size of Iceland's footprint and find out if those reasons – if found – could help us come to some broader understanding about the biases of the EF standard method. At the same time there was no specific theory or hypothesis to test and by that the thesis stayed close to the ideal of not tainting the research with preordained theoretical ideas that might bias the results (Eisenhardt, 1989).

Case selection is an important step in case studies and random selection is *"…neither necessary nor preferable"* (Eisenhardt, 1989 p.537). According to Pettigrew, 1988 extreme cases that clearly highlight the phenomenon under study should be given preference. This thesis follows this route by choosing Iceland, the most extreme case known in the GFN's NFA accounts. Iceland is thus not only an extreme case but also a critical case as defined by Flyvbjerg, 2006, where general lesson can be inferred from the case under study.

3.1.2 One-factor-at-a-time

Initially a comparison of two editions of the GFN Learning License Workbook were compared to highlight sensitive areas and measure the EF of the subject – Iceland. Identified sensitive areas were then scrutinized, initially using one-factor-at-a-time (OFAT) method, where each experimental run was focused on isolating one variable while others are kept constant (Frey et al, 2003). Since OFAT cannot show how different variables can interact with one another the research continued by combining changes in variables (cells) to identify the combined impact on the results and illustrate error margins and uncertainty levels involved with the calculations.

3.1.3 Data analysis

As the research progressed a recurrent theme came to be one of uncertainty - uncertainty in input parameters as discussed by Parker and Tyedmers (2012) in their investigation of MF. Intensive, exploratory, pragmatic, manual data analysis turned up a variety of errors, estimates and inaccuracies which formed the foundation of the hypothesis that EF standard method, using international databanks suffers from high levels of uncertainty.

Further discussion on the choice and validation of methods used can be found in chapter 5.

3.2 Data

Multiple data collection methods were utilized for the thesis. In order to obtain the most accurate data, the data collection not only relied on statistical quantitative data but also incorporated qualitative methods such as interviews and talks with various specialists. This *"…combination of data types can be highly synergistic"* (Eisenhardt, 1989 p.538) which strengthens the work as described by Mintzberg, 1979. Data collection methods were not fixed but followed what Eisenhardt, 1989 calls *"controlled opportunism"* where the research is allowed to shift focus to different aspects of the research as more information is garnished and new insights are gained. This allows flexibility in data collection in order to gain deeper understanding of the case under investigation. This leads to in case analysis in papers II and III where the focus is put on certain aspects of the Icelandic EF (MF and CF). Some cross-case analysis is also utilized in paper I and to a lesser extent in paper II but for the most part the focus is on Iceland as a case.

4 Results

The three articles making up the thesis body all deal with different aspects of the same research question and therefore form a coherent whole. The findings are unanimous in that data uncertainty is found to be of utmost importance in EF calculations and due to their great sensitivity, an error in a single datapoint can have large scale impacts on the results. MF and CF show up as particularly prone to error - MF for sensitivity and CF for lack of reliable data. Further it is found that international databanks are not robust enough to supply data with enough accuracy for the accounts. The risk of misleading results is therefore high. Hence, great care needs be taken when calculating EF – and not least when interpreting results. Results should always include caveats and assessments of uncertainty levels. Calculations without error margins cannot be considered reliable.

Further causes of bias in data are also apparent; data availability, a lack of unified global methods to measure certain natural phenomenon and a lack of knowledge of natural systems. Under these conditions use of estimates and averages becomes necessary but at the same time seriously undermines the level of accuracy of the accounts. In the case of data gaps, estimates are, all the same, found to improve the accounts.

The findings show that highly specialized economies can be used to identify biases and errors by showing up exaggerations in results. This was used successfully in the three articles by focusing on Iceland as a case study. The bias identified are equally applicable to all national EF accounts, but errors can be harder to identify in more complex economies due to different errors working in opposite directions and cancelling each other out – and thus getting lost in the noise of more economic complexity.

In the case of Iceland MF and CF jump out as “hotspots” where great uncertainty is involved in the calculations and sensitivity is high.

The uncertainty involved in the calculations makes full disclosure and use of caveats particularly urgent in dissemination of results. The thesis finds that this is rarely done in dissemination of EF results nor in educational material coming from GFN.

Continued work on improving EF an as indicator is highlighted as a positive attribute but an inferred notion is that methodological improvements are not likely to yield great results if the data used is not at adequate quality levels.

Table 1. gives an overview of the three studies and their findings. In the top box the research question is stated, pointing to the three papers it spawned. The matrix details the paper’s titles, their aims and their key findings. This leads to the conclusion shown in the box at the bottom.

Table 1 Overview of papers and their findings.

RESEARCH QUESTION
What can Iceland, as an outlier in EF standard method accounts, teach us about the uncertainty involved with the calculations?

	Paper I	Paper II	Paper III
Title	Standard Ecological Footprint method for small, highly specialized economies	Increasing the accuracy of marine footprint calculations	Data accuracy in Ecological Footprint's carbon footprint
Purpose	To analyse the EF standard method and the potential biases and errors when applied to a small and highly specialized economy	To identify errors and sources of bias and search for ways for improvement of the marine footprint component of EF	To assess uncertainty involved in EF carbon footprint calculations with a focus on data quality for the production variable of the CF equation
Key finding	Although the indicator's accuracy has been much improved in recent years, additional improvements are still needed. The extremes of the Icelandic economy highlight errors to the extent that the huge footprint the calculations yielded make the country an outlier in a global context. The indicator seems in this respect not able to deal with such a degree of specialization, especially where the main sectors are very large in relation to the population	The paper highlights the importance of data accuracy and identified data gaps as the largest source of bias. The paper further illustrates how relatively few and minor inaccuracies can have detrimental effects on the results. The use of local data and actual hard data as opposed to general estimates are also shown as important, especially for known areas of sensitivity such as trophic levels, discount rates and biocapacity	Averages and estimates play a major role in GFN's CF calculations mainly due to the use of IPCC default emission factors. Further, activity data from international databanks rarely match locally sourced data. The change in CF under the data scenarios created range from a 42% decrease in CF to a 147% increase. Relevant caveats regarding estimations in CF calculations are found lacking in GFN's dissemination of results

CONCLUSION
EF calculations under the standard method are highly sensitive, with minor errors able to radically change the outcome of results. Several "hotspot datapoints" should be recognized in this context. Input data becomes of utmost importance under these conditions. Calculating EF with insufficient data can thus lead to very misleading results. Data from international databanks does not seem robust enough to yield

realistic results when used in EF calculations. Great caution should therefore be exercised when calculating EF and not least when assessing results. Results that do not include uncertainty assessments should be disregarded.

The first calculation of the Icelandic EF made for this thesis (paper I) yielded a footprint of 56.59 gha – almost six times larger than the largest published footprint globally in that year, which was for the United Arab Emirates, 9.46 gha. The two most outstanding features of the Icelandic calculations were fisheries being responsible for 97% of the footprint and carbon footprint being non-existent. Table 2, below, taken from paper I, shows the results from the thesis' first calculation of the Icelandic EF.

Table 2. EF and biocapacity of Iceland, per capita, 2008 edition results

Land type [-]	**Production** [gha]	**Imports** [gha]	**Exports** [gha]	**Consumption** [gha]	**Biocapacity** [gha]
Cropland	0.07	0.51	0.02	0.56	0.02
Grazing land	0.46	0.00	0.02	0.44	0.46
Forest	0.00	0.54	0.00	0.54	0.03
Fisheries	62.67	1.32	9.38	54.61	17.32
CO_2 uptake l.	2.77	8.71	13.19	0.00	0.00
Built up land	0.44	-	-	0.44	
Total	**66.40**	**11.09**	**22.60**	**56.59**	**18.26**

What seemed like minor improvements to the GFN Learning License Workbook then yielded major changes to the results of the Icelandic footprint. Using a different edition of the workbook but the same data, Iceland's footprint dropped from 56.59 gha to 25.26. The main changes occurred within the two hotspots already identified: fisheries and carbon footprint. The fisheries footprint dropped from 54.61 gha to 12.57 gha, due mainly to a better coverage of extraction rates for exported goods, changes to trophic levels of key species and a change made to an aggregation error, that happened to match the Icelandic situation. CF went from 0 to 10.74 gha. due to the 2014 edition using local CO_2 intensities for exports as opposed to global averages as the 2008 did. Table 3, below, also from paper I, shows the results from the calculations of the 2014 Learning Licence Workbook.

Paper I answered the research question "How well does EF standard method handle a small, highly specialized economy and what are the main sources of bias?" by confirming the findings of Jóhannesson, 2010 and showing how the economic specialization and the relatively small population of Iceland, compared to the size of its economic activities, cause errors to compound to the extent that results become non-sensical. The main sources of bias were identified as MF and CF.

Table 3. EF and biocapacity of Iceland, per capita, 2014 edition results

Land type [-]	**Production** [gha]	**Imports** [gha]	**Exports** [gha]	**Consumption** [gha]	**Biocapacity** [gha]
Cropland	0.05	0.85	0.09	0.81	0.02
Grazing land	0.41	0.00	0.19	0.22	0.41
Forest	0.00	0.54	0.00	0.54	0.03
Fisheries	63.16	5.59	56.18	12.57	17.31
CO_2 uptake land	2.59	10.22	2.08	10.74	0.00
Built-up land	0.38	-	-	0.38	0.38
Total	**66.59**	**17.20**	**58.54**	**25.26**	**18.15**

Further analysis of MF (paper II) highlighted various issues that had considerable negative impact on the reliability of the results. These included:

- Data gaps
- Uncertainty regarding trophic levels
- Uncertainties regarding global averages vs. local figures for discount rate
- Discrepancies between local consumption data and international databanks

Closing data gaps - in this instance gaps in yield data for traded goods due to missing extraction rates - with estimates based on extraction rates for closely related products or even averages of available national extraction rates - lowered MF from 22.26 gha to 4.57. Uncertainty regarding trophic levels (TL) highlighted the sensitivity of the calculations. The Fishbase data used under SM are averages from all over the world that do not take into account local conditions – nor the fact that no globally accepted method of estimating TL exists. Updating the data used for the calculations from the 2016 Fishbase data to the 2017 data led to a change in MF from 22.26 gha to 16.82. This was almost entirely due to a change in TL for cod from 4.1 to 4.42. Using local data dropped MF to 10.38 gha. Discount rate (DR) under SM is a constant 27% for all species. Using averages for cod and haddock based on local estimates from Iceland (1.1%) took MF from 22.26 to 18.11 gha. When all these changes were combined, MF dropped to 0. A different calculation of MF based on national surveys of fish consumption (Steingrímsdóttir et al, 2014) yielded a result of 0.67 gha thus highlighting problems with calculations based on data from international databanks. These changes, in their various combinations, are shown in table 4 below, taken from paper II.

Table 4. NFA 2017 MF results for Iceland and effects of various changes to input data

Version	**Production**	**Imports**[4]	**Exports**	**Total MF**
NFA 2017	46.67	1.91	26.31	22.27
Local area size figures	46.63	1.91	26.29	22.25
TL Fishbase 2017	34.71	1.91	19.80	16.82
Local DR (1.1%)	37.14	1.91	20.94	18.11
TL Fishbase 2017 + local DR	27.65	1.91	15.78	13.78
Extr. data gaps estimates	46.67	1.91	44.01	4.57
Extr. est. + TL Fishbase 2017	34.67	1.91	30.14	6.44
Extr. est. + Local DR	37.17	1.91	35.85	3.23
TL F.2017 + Local DR + Extr. est.	27.62	1.91	23.60	5.93
Local TL (P&V,2000)	20.59	1.91	12.12	10.38
Local TL + Extr. est.	20.62	1.91	24.21	-1.82
Local TL + Extr. est. + DR	16.42	1.91	20.07	-1.74
EF based on UNR/DoH survey	0.67	0.01	0.01	0.67

Paper II answered the research question “What are the main sources of bias within the marine footprint component of EF and how can it be mitigated?” by confirming and quantifying the known uncertainties involved in trophic levels and discount rates as well as showing the impacts of data gaps and how these can be mitigated with careful estimates. A key source of bias was further found to be input data.

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[4] Since most changes involve local data, imports were kept unchanged.

Further analysis of CF (paper III) highlighted a variety of uncertainties involved in the calculations, including:

- Uncertainties in input data
- Large standard error for the key constant AFCS
- Uncertainties regarding the key constant OSfr
- Uncertainties regarding knowledge of natural processes in carbon emissions

International databank data rarely matched locally sourced data and when those differences were combined with the defined standard error in average forest carbon sequestration rates (AFCS) used under SM as well as the upper and lower limits of ocean sequestration fraction (OSfr), to create case scenarios, the change in CF ranged from a 42% decrease to a 147% increase. Lowering the AFCS by the standard error only, yielded a 96% increase in CF. The paper also found considerable uncertainty in relation to our knowledge of natural processes in carbon emission which further expounds the uncertainty involved in the calculations.

Figure 1, below, taken from paper III, is a graphic illustration of how the CF calculations are set up, estimated data points and the percentage difference between GFN data (International Energy Agency (IEA) – data) and local data. Green indicates data points that are within a 10% difference between GFN data and local data, orange indicates data discrepancies above 10% and red indicates estimated data points. Descriptive boxes are left uncoloured and blue indicates data not assessed. The blue frame denotes the scope of the study (EQF is outside the scope of the study but for clarity's sake is inside the blue frame since it is a part of the footprint intensity of carbon in the calculation matrix).

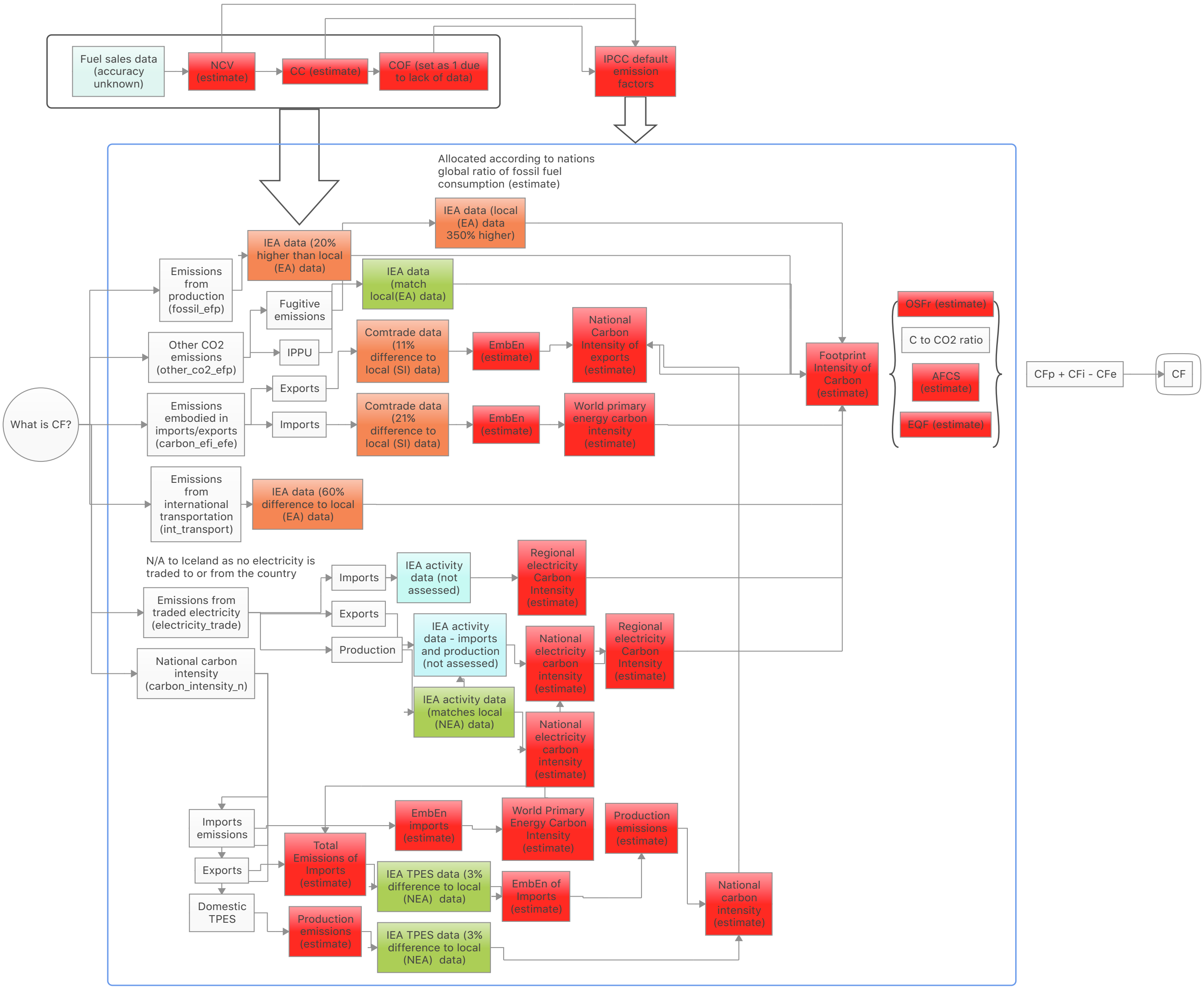

Figure 1 Graphic illustration of CF calculations

In figure 2, below, taken from paper III, results from sensitivity testing through case scenarios are presented as a percentage change.

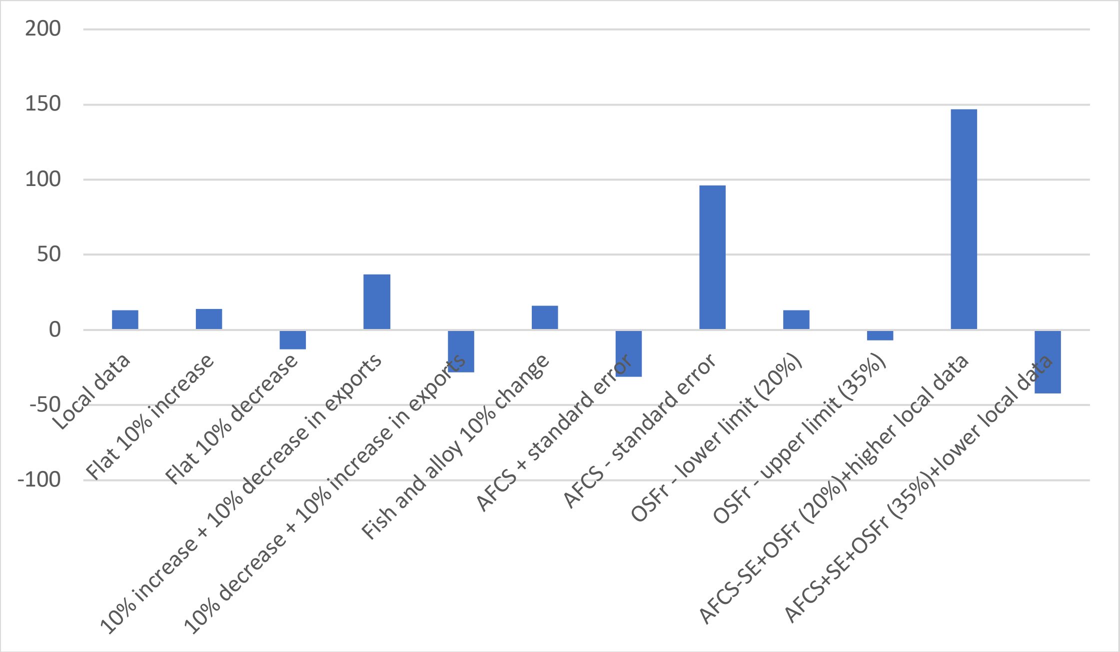

Figure 2 Percentage change to CF under different scenarios of data variance

Paper III answered the research question "What is the uncertainty involved with carbon footprint calculations in regard to the production variable?" by showing how input data, key constants and a lack of knowledge of the natural processes behind CO_2 emissions accounting, individually and in combination are responsible for high levels of uncertainty involved in the calculations. Quantification of the variation in results depending on different scenarios was also provided.

5 Discussion

This chapter discusses the results, in light of the published literature, and various thoughts and considerations the results invoke as well as evaluating the thesis and its contribution in academic and practical terms and assessing its validity, reliability and limitations.

5.1 Results and their meaning

The aim of this thesis was to assess the uncertainty involved in Ecological Footprint standard method calculations, identify areas of sensitivity and look for ways of improvement with the research question defined as:

What can Iceland, as an outlier in EF standard method accounts, teach us about the uncertainty involved with the calculations?

This was done with a detailed analysis of EF calculations using Iceland as a case study. Quantitative methods were utilized for the data assessments and results interpreted through qualitative means. The results of all three papers indicate that EF calculations under the standard method involve a high degree of uncertainty. The thesis attempted to quantify this uncertainty and in the papers the difference between an old value and a new one is often shown as a percentage change – from the old value to the new. It could also be argued, since the new value is also an estimate as is the old one, the difference between the two should be shown and not the change from one to the other – therefore a percentage difference should be presented. Figure 3 details the quantified uncertainty detected in the three papers both the percentage change and the percentage difference as well as the change in gha.

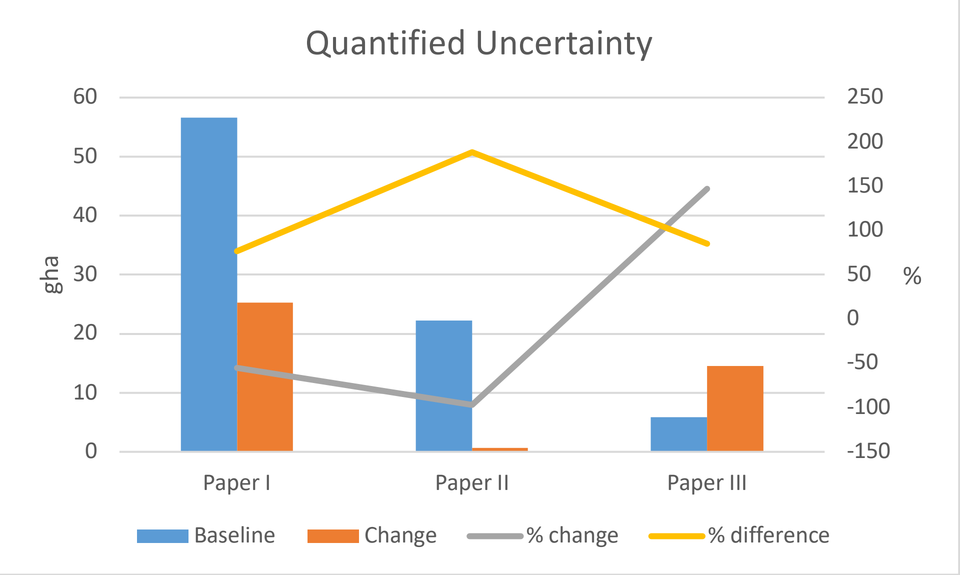

Figure 3 Quantified Uncertainty in papers I – III

Quantified percentage change ranges from -55% to +147%, with the greatest change being found in paper III for CF. Percentage difference ranges from 77% - 188%, with the greatest difference being found in paper II for MF. The highest change in a single datapoint shows up in paper III for fugitive emission with a 350% change from data from international databanks and local data. Filling data gaps with estimates led to a change in results of -79% in paper II with the difference between the two figures being 132%.

The reasons for the inaccuracies were identified as threefold:

1. Discrepancy between local and international data sources
2. Lack of knowledge of natural systems and processes
   a. Which results in data gaps
   b. Or leads to use of estimates
3. Aggregation and use of averages

The findings show that the calculations are very sensitive, making data accuracy of great importance. MF and CF show up as being particularly prone to error and international databank data are found to involve uncertainty to the point of being of little use in such sensitive calculations. It is further found that the uncertainty involved in EF calculation is rarely made explicit.

5.1.1 Theoretical and practical importance

Although Iceland is used as a case study throughout, the nature of the uncertainty is not case specific and as such therefore applies to all EF accounts using the standard method. Due to Iceland's relative economic specification, errors are highlighted in results whereas for countries with a more varied economic foundations the same errors may be drowned in the noise of the data. The academic importance of the work is therefore considerable and general – i.e., applicable to any national EF account. The thesis shows the dangers in blindly trusting data from international databanks when calculating EF for a nation according to the standard method, as defined by GFN, and gives clear examples of the scale of the errors that can be involved. Further it shows the main areas of sensitivity and bias within MF and CF and thus is important for any nation with those land types of considerable sizes – although it applies to any country with any activity in either of those land categories (which includes all countries) – but the larger these sectors are, the larger the error is likely to be affecting the final result.

The implications of the thesis for practical use of the indicator such as in policy setting – or even dissemination - should be clear. For any policy use, the results of the calculations need to be scrutinized thoroughly – in a similar manner to what is done is this work – for all land types. Local data of high quality should be secured, and sensitivity tested. Uncertainty levels need to be assessed and clearly stated with all publicity of results. The same precautions hold for dissemination and educational use of the indicator. The sensitivity of the accounts makes them vulnerable to abuse and misuse – such as for political or propaganda purposes – and the only way to counteract such activities is with a clear demand for full transparency regarding the uncertainty and limitations involved in the method and calculations.

5.2 Validity, reliability and limitations

The following is an inquiry into the validity, reliability and limitations of the thesis. Validity considers if the research is actually measuring what it intends to measure while reliability refers to repeatability and if the same results will be had with multiple reconstructions. The discussion of limitations attempts to assess where the thesis may fall short due to the assumptions made, scope of thesis, methods used etc.

5.2.1 Thesis validity

Using Ruane's (2004) system of assessing validity, the thesis' internal validity is robust since the three conditions of causality (temporal order, association and non-spuriousness) between dependent and independent variables – input data and results - are effectively satisfied. Being that EF is a standardized, tried and tested method, honed for years through experimentation ensures this. External validity is also strong since the thesis' results are applicable to any EF study at the national level using the standard method and international databanks. The likelihood that the bias highlighted by this research may easily go undetected in less specialized economies than used for this thesis, gives the work added value.

The case study method, as utilized here, via an in-depth study of a single case, has often been considered to give insufficient information on the issue in general since the scope of the study is too limited (Abercrombie et al, 1984; Campell and Stanley, 1966). Flyvbjerg, 2006 on the other hand, showed how this "conventional wisdom" on the use of the single case study was based on five misunderstanding:

1. "General, theoretical (context-independent) knowledge is more valuable than concrete, practical (context-dependent) knowledge.
2. One cannot generalize on the basis of an individual case; therefore, the case study cannot contribute to scientific development.
3. The case study is most useful for generating hypotheses; that is, in the first stage of a total research process, while other methods are more suitable for hypotheses testing and theory building.
4. The case study contains a bias toward verification, that is, a tendency to confirm the researcher's preconceived notions.
5. It is often difficult to summarize and develop general propositions and theories on the basis of specific case studies." (Flyvbjerg, 2006, p. 3-4)

Flyvbjerg goes on to dismantle these arguments – or misunderstandings – one by one. Flyvbjerg argues that concrete, context-dependent knowledge as can only be created by a case study is of more value than general, theoretical knowledge – basing his arguments to an extent on the same conclusions reached by scholars such as Campell, 1975 and Eysenck, 1976 who both had been proponents of the idea that case studies were of little use in scientific inquiry but had both later made a complete reversal in their thinking on the matter: *"...sometimes we simply have to keep our eyes open and look carefully at individual cases - not in the hope of proving anything, but rather in the hope of learning something!*" Eysenck, 1976, (p.9) wrote.

When attacking, what he labels, the second misunderstanding - that of the single case study being unable provide arguments for generalization - Flyvbjerg enlists the company of no lesser researchers than Galileo, Newton, Einstein, Bohr, Darwin and Freud among others, who's development and work depended on the method. Flyvbjerg also quotes W.I. B. Beveridge, 1951 (from Kuper and Kuper eds. 1985, p.95) who said: *"[M]ore discoveries have arisen from intense observation than from statistics applied to large groups.*" and reaches the conclusion that formal generalization is overvalued while "*the force of example*" is underestimated. Thus, diving deeper into single cases can be more informative than a more superficial study of broader samples.

The third misunderstanding is based on the second – i.e., because one can't generalize on the basis of a single case study it can only be used in the formation of hypothesis but not for hypothesis testing and theory-building. Being that the second misunderstanding has been dismantled the third therefore crumbles. This is in line with Harry Eckstein, 1975 who argued that case studies are valuable at all stages of the theory building process but most valuable at hypothesis testing stages as opposed to the, possibly, generally held view that they are only useful for hypothesis building.

How much information can be garnished from cases can be increased by their strategic selection.

> *"When the objective is to achieve the greatest possible amount of information on a given problem or phenomenon, a representative case or a random sample may not be the most appropriate strategy. This is because the typical or average case is often not the richest in information. Atypical or extreme cases often reveal more information because they activate more actors and more basic mechanisms in the situation studied."* (Flyvbjerg, 2006, p. 13)

Flyvbjerg separates cases selected randomly, to avoid systemic biases in the sample, from cases that are chosen with the view to maximize the information to be garnished with what he labels "*information-oriented selection*". These he then divides into four categories: Extreme or deviant cases, maximum variation cases, critical cases and paradigm cases. Table 5 details these categories.

Table 5 Flyvbjerg's strategies for the selection of samples and cases

Type of selection	Purpose
A Random selection	To avoid systematic biases in the sample. The sample's size is decisive for generalization.
1. Random sample	To achieve a representative sample which allows for generalization for the entire population.
2. Stratified sample	To generalize for specially selected sub-groups within the population.
B Information-oriented selection	To maximize the utility of information from small samples and single cases. Cases are selected on the basis of expectations about their information content.
1. Extreme/deviant cases	To obtain information on unusual cases,

	which can be especially problematic or especially good in a more closely defined sense.
2. Maximum variation cases	To obtain information about the significance of various circumstances for case process and outcome; e.g., three to four cases which are very different on one dimension: size, form of organization, location, budget, etc.
3. Critical cases	To achieve information which permits logical deductions of the type: "if this is (not) valid for this case, then it applies to all (no) cases.”
4. Pragmatic cases	To develop a metaphor or establish a school for the domain which the case concerns.

The fourth misunderstanding holds that the case study method mainly serves to confirm the researcher’s preconceived ideas. Flyvbjerg explains how the work of academics such as Campbell, 1975, Ragin, 1992, Geertz, 1995 and Wieviorka, 1992, as well as his own research into intensive, in-depth case studies, shows that researchers using the method often change their hypothesis due to the case study work and findings and thus find that their preconceived ideas are tested and proven wrong by the case study. Based on this Flyvbjerg stipulates that the case study method not only is no more biased toward verification of researchers preconceived notions than other methods but is actually biased towards falsifying such notions and ideas.

The fifth and last misunderstanding Flyvbjerg defines is on how it is often difficult to summarize and develop general propositions and theories on the basis of specific case studies. Here Flyvbjerg basis his argument on the importance of narrative as a tool humans use to experience and understand the world around them. His conclusion is that:

> *“It is correct that summarizing case studies is often difficult, especially as concerns case process. It is less correct as regards case outcomes. The problems in summarizing case studies, however, are due more often to the properties of the reality studied than to the case study as a research method. Often it is not desirable to summarize and generalize case studies. Good studies should be read as narratives in their entirety.”* (Flyvbjerg, 2006).

Although Flyvbjerg’s point of view is that of a social scientist, mainly working with qualitative research his findings fully apply to the method used here, where qualitative interpretation of results is based on quantitative data analysis. In fact, Flyvbjerg doubts the validity of the sharp separation between quantitative and qualitative research methods as its often presented in the literature and advocates for a problem driven approach, where the methods used are based on the needs of the problem at hand - as opposed to a method driven one. A combination of the two approaches Flyvbjerg finds if often the most appropriate way to solve the problem.

As stated, this thesis uses a combination of the two approaches with the case selection being information-oriented and thus falling under section B in table 2 above. The case of Iceland is chosen for being an extreme case and as such, exceptionally helpful in highlighting methodological and data accuracy issues. Further, Iceland is a critical case, and a logical deduction can safely be made that the issues that make Iceland an extreme case also apply to other cases but it's only the particulars of the Icelandic case that highlight the issues that otherwise apply to all EF standard method calculations. The single case study method used for this work is thus selected based on B 1 and 3 in table 2 above.

5.2.2 Thesis reliability

The validity of the thesis has been dealt with above. While validity refers to accuracy – is the study measuring what it is supposed to measure - reliability refers to reproducibility – will repeated measurements yield the same results? As Healy and Twycross, 2015 point out, reliability is impossible to measure and can thus only be estimated.

Given that the same tools, same methods and same data are used as done in this thesis, the results should never change, so in the classic sense the reliability of the work is very high. Any deviation from those, on the other hand, will invariably change the outcome – and as the thesis shows, even minor changes can have a big impact on the outcome, due to the sensitivity of the accounts.

5.2.3 Thesis limitations

This thesis relies on the assumption that, since international databases gather their data from local sources around the globe, data gathered locally should be more robust. Should this assumption be wrong, a foundational argument of this thesis crumbles. In that case estimating accuracy of the input data used under the standard method by comparing it to what is assumed to be the most accurate data available would have no meaning. In that sense this thesis suffers from the same limitation as EF calculations in that it relies on assumptions and data from outside sources and the accuracy of such data can often be very difficult to verify by the researcher.

Local data used for the thesis thus involves uncertainty that is not assessed by this work. That is, the data commonly used for EF under the standard method – data from international data banks – are to an extent assessed but no thorough assessment can viably be made of the local data used to correct the data from the international databanks. In the context of the thesis this is not an important issue since the local data are being used to highlight the uncertainty involved in the commonly used data and are not under assessment themselves. Furthermore, the results of the EF measurements are not important either as such but serve to assess the accuracy of the data and the calculations in general.

Another limitation is that the thesis does not cover all land types used in EF in detail and only MF and CF are scrutinized thoroughly in separate papers (II and III) with other land types being dealt with in a more general manner (paper I). Due to time restrictions only the areas showing up as most sensitive were under analysis and therefore cropland, grazing land, forests and built-up land are not analysed in the same manner as fisheries and carbon uptake land. A similar analysis of these land types would make for interesting further research. Further, although the thesis utilizes a case study scenario, no absolute statements are – or can be made – on the EF, MF or CF of the case in question. The purpose of the case study is thus to be a vehicle for analysis of the data and calculations involved and only to a much lesser extent illuminate conditions regarding the footprints of Iceland. Like any other EF study using the standard method the case results are estimates – an indication as the name of the tool suggests – and should only be viewed in such a light. The case study is all the same fully relevant in revealing the uncertainty involved in the calculations and as such fully applicable to other nations. As such the case study functions as it should.

The methods used for the thesis developed alongside the thesis itself and therefore were tailored to the needs of the issues at hand at any given time. This avoids the limitational problems that may arise when using a pre-fixed method to deal with a problem – that of fitting squares into round holes. This effectively eliminates potential methodological issues with the methods used such as the lack of generalizability of the single case study.

Thus, although, the single case study method has often been criticized for a lack of generalizability – in spite of this criticism having been refuted as discussed in chapter 5.2.1 - the generalizability of this work is clear since the case of Iceland is used here to highlight general methodological, data and calculation issues with EF standard method and not purely to assess what might be a more precise EF for Iceland. This makes Iceland a critical case according to Flyvbjerg, 2006, a case where general lessons can be learned.

A possible limitation could be found in sensitivity testing which is done randomly and manually through OFAT in the thesis and not via computerized global system such as Monte-Carlo technique. Some scholars have found OFAT deficient as a method to analyse sensitivity (Saltelli and Anonni, 2010; Saltelli et al, 2019) while others find that its utility is really case dependent (Frey et al, 2003; Tian, 2013). For the purposes of this study OFAT served its purpose of highlighting the sensitivity involved in the EF calculations and giving a perspective on the magnitude of the issue. Sensitivity testing in the thesis is thus only intended to give examples of possible error magnitudes but is by no means a thorough or a complete test of sensitivity within EF calculations. A global uncertainty and sensitivity analysis would no doubt provide a deeper understanding of the issues dealt with in the thesis.

In light of these limitations, further research could include a thorough examination of the remaining land types for Iceland; forests, cropland, grazing land and built-up land. This, or these, studies would conclude the work that has been started here and would give a fuller picture of the uncertainty levels involved with EF accounts on the whole. Studying other cases – other nations – in a similar manner would also further clarify the picture of uncertainty in EF and how and if the differences between local circumstances manifest in the results. Research into specific aspects of uncertainty raised by the thesis would have a clear scientific value. These could be local in nature – such as research into local trophic levels and marine food webs – or global – such as studies of how trophic level estimates could be normalized globally. Any of the many uncertainty factors highlighted by the thesis provides opportunity for further research in this manner, both on local and global levels. A logical next step would also be a quantitative global uncertainty and sensitivity analysis on the Icelandic accounts, particularly CF and MF.

5.3 Other issues and thoughts on EF raised by the thesis

Questions of the validity of EF were discussed in chapter 2. These questions are still left unanswered – or at least debated and not agreed on as the chapter indicates. This disagreement is documented in Galli et al, 2016, where GFN associated and a couple of EF's harshest critics answer ten questions, with each party deciding five of those ten questions. The article is a laudable attempt by the two camps to join forces in moving the debate forward in a civil manner but still, arguably, highlights further the two different perspectives and shows how the debates described in chapter 2 of this thesis do not seem to have changed either party's mind on much of anything regarding the method, its shortcomings or its utility.

5.3.1 Use of metaphor

A core aspect of the criticism aimed at EF has been regarding its metaphoric basis. Without being explicitly stated to a certain extent the debate has largely evolved around the unspoken question: "Is the use of metaphor valid in scientific undertaking?". Fred Luks, 1998 argues that metaphors are not only valid but necessary – especially for the relatively new field of ecological economics. Luks argues that metaphor is needed because as Lakoff and Johnson, 1980 claim, it is through metaphor humans reach their understanding of their experiences and shape their conception of the world. Klamer and Leonard, 1994 (p.31) put it: "*Science needs metaphor since it provides the cognitive means to chart the unknown*". Luks points to the work of McCloskey, 1994 who suggests that good writing is often viewed with suspicion by economists because it indicates that *"...the writer is not a Scientist*" (McCloskey, 1994, p.125) and that scientist often attempt a style that is free of rhetoric in order to send the message: "*I am a Scientist: give way.*" (McCloskey, 1994, p.122). Luks argues that this style is no less rhetorical than use of metaphor. Luks is pointing to the necessity for ecological economics to use metaphor and visions to affect the political arena and reach an audience beyond the academic community. Luks agrees with Klamer and Leonard, 1994 and McCloskey, 1995 that neoclassical economists – who to a large extend shape public discourse on economic, environmental and political matters – frequently use metaphors such as the invisible hand, equilibrium, price mechanism etc. "*Rhetoric of inquiry is needed precisely because facts themselves are mute. Whatever the facts,* we *do the speaking — whether through them or for them*" (Nelson et al., 1987, p.8; their emphasis). This is why ecological economics can't rely on facts and figures to speak to the public but need metaphor that resonates with the human experience, according to Luks.

Arguably, this is precisely what EF has managed to do. EF's central metaphor is, in the words of van Vuuren and Smeets, 2000 (p.127): *"...probably the most important reason for its popularity: i.e., expression of the impacts of human consumption in terms of a visible footprint made on the natural carrying capacity...*". This evokes a spectre (using a classic economic metaphor[5]) of an issue raised by the thesis, that of the line between science and activism, if the two go hand in hand or if there needs to be a separation between the two. This thesis argues for the latter. This does not undermine Luks argument

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[5] "A spectre is haunting Europe—the spectre of communism." (Marx and Engels, 1848).

but does question the reasoning behind his urging ecological economics to use metaphor – that of affecting policy and public opinion. If fact, EF may just provide a cautionary tale in this respect.

EF's success in reaching the public and politics is largely uncontested (Galli et al, 2016; van den Bergh and Grazi, 2015; Giampietro and Saltelli, 2014; Venetoulis and Talberth, 2008; Binningsbo et al, 2007) and as pointed out by van Vuuren and Smeets, 2000 this is most likely due to their successful use of metaphor. At the same time the method has been heavily criticised for a supposed lack of scientific credibility, as detailed in chapter 2. Further, GFN has been criticised for not responding to criticism and thus hindering further development of EF as a sustainability indicator (van den Bergh and Grazi, 2013; van den Bergh and Grazi, 2015).

As explained in paper III a likely cause for this friction are the contradictory needs of scientific inquiry on the one hand and an operating NGO/think tank on the other. The operations of NGOs and think tanks are likely reliant on staff, offices and a variety of overheads that need to be paid off with approved currency. Ideals won't pay the bills. Under these well-known and practical conditions, it is understandably difficult to build and maintain the operations without being able to deliver a consistent message and a reliable product. Even the best-known brands in the world, say Coca Cola, would hardly fare well if their product was ever changing[6]. Arguably, the scientific exploration has thus suffered for the successful outreach work done by GFN.

It is for this reason that science should always be conducted for science's sake and free from attachments to ideologies, business ventures, political ambitions etc. By mixing the wish to improve the world with the task of measuring human impact on the natural environment GFN has possibly done, what seems like such a useful tool for dissemination of environmental issues, a disservice by hindering its development within academic circles by being such a powerful force within the "EF community". In business speak it could be said that GFN took the product to market too soon - while still in development - which has caused a backlash in that a group of academics have risen on their hindlegs and heavily protested the use of EF in any serious context, which has undoubtedly affected EF's reputation, at least within academic circles.

This mixing of ideology, politics or business with science is naturally not only dangerous for EF or ecological economics but any venture that attempts to mix the two. Paper III suggests that leading institutions such as the IPCC may in a similar manner be compromised by attempting to ride two horses at the same time – those of science and politics. Recently the World Health Organization (WHO) has been under attack from various directions and this raises questions regarding these issues. This "polluting" of science can be particularly dangerous when practised at the level of international institutions and may lead to a certain kind of authoritarianism in science.

This was for instance recently reflected in YouTube - a company most would consider an open internet platform for exchange of ideas - announcing that all content that is not in line with the views of WHO will be deleted on the grounds of it being misinformation (BBC News, 2020). Here the freedom of speech and exchange of ideas is limited to what is

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[6] This does not take into account planned obsolescence which is a different thing and not under review here.

deemed the official – the one correct – narrative. The truth is of course that science is a process, a method, an approach – and scientific knowledge is rarely fixed or at an end point. Scientists therefore invariably disagree – on almost everything that falls under the domain of science (and probably much of what falls outside it too!). Science also often develops most through conflict – when conflicting ideas challenge each other in their search for the truth. Therefore, the more room we create for debate, for ideas and arguments to be viewed, the better for society, not worse.

People have, since they developed the ability, always talked to one another. Some have had unorthodox views, radical even – crazy some might even say. This has not been a reason to censor speech. To attempt to stop people talking under the guise of science and that only the official narrative can be allowed to be heard – because everything else is deemed unscientific – is a gross misuse of science. This is a slight tangent put forth here to reiterate the point that science must be conducted for the sake of science – in search of knowledge and understanding – and there is no way to objectively infuse such undertaking with ideology, politics or business without jeopardizing the integrity of the search.

But to return to the issue of metaphor use, it is worth noting that EF is not the only concept within ecological economics to employ metaphor. One successful concept that readily springs to mind is that of planetary boundaries (Rockstrom et al, 2009). This hugely successful concept uses the metaphor of thresholds that are not to be crossed wishes one to remain within the limits of sustainability. These two, EF and the planetary boundaries concept are likely the best-known concepts to come out of ecological economics – which is probably indicative of the power of metaphor in ecological economics. Of the two EF has, arguably, a much wider reach among audiences outside academia. These last statements are purely speculative and a simple study to confirm this hypothesis might be worthwhile to understand the power of the EF metaphor, which seems considerable.

5.3.2 The troublesome CF

The EF method's reliability has been dealt with in some detail in chapter 2. As indicated there, there are still various issues that affect the method's reliability. CF is especially highlighted there as particularly controversial, with numerous issues contested; the hypothetical nature of the EF is questioned; uncertainty is not made explicit; aggregation issues are pointed out and the fact that globally EF shows no overshoot if CF is not included in the accounts is stated. This last point has been argued by GFN on the grounds that it is the accumulative effect of all the land types that causes the overshoot and therefore taking one of the essential parts out will not portray the full picture (Lin, 2020).

The question remains if CF is really an essential part of the EF? For one, CF covers the only sink aspect of the accounts. All other land types cover resource depletion. One argument for not including CF in the account is that it would make the indicator more internally coherent – it would be a tool focused on measuring resource depletion. Another argument for excluding CF is the data issue brought up by this thesis. Because of the estimations involved with CF calculations and data, the results are highly debatable. Seeing as how large the share of CF often is in the whole EF accounts the uncertainty involved with the CF clearly has a great effect on the final EF results. Excluding CF would in this way immediately help increasing the accuracy of the accounts.

The arbitrary way CF is estimated has also been criticised, as detailed in chapter 2, with GFN associates responding that forests are the only ecosystem to sequester CO_2 in a substantial way (Wackernagel and Silversteen, 2000) and that *"...(EF) accounts for competing demands on limited biologically productive space. One competing demand is waste absorption (based on the widely accepted assumption that increasing CO_2 concentration in the atmosphere is leaving a burden to future generations).*" (Lin et al, 2015 p.466). In a recent study. Zhu et al, 2016 show how the earth became greener over the timespan of their study - the years 1982 – 2009. The study found that 70% of the greening was due to increased CO_2 in the atmosphere. If CO_2 leads to more greening, in a considerable manner, according to the study, what effect does that have on sequestration in the long run? How could EF account for that? Or should CO_2 not be considered to be competing for demand on biologically productive space but as growing the resource base?

Excluding CF from the accounts would also address another contested issue, namely that of implicit weights and aggregation problems – although it would not eliminate the problem since EF – in its current form - is a composite indicator delivering results in a single figure. All the same, CF has been particularly pointed out in this regard (van den Bergh and Grazi, 2013).

As mentioned above, dropping CF from the EF accounts would make the accounts more coherent internally since no waste streams would be included. This would in turn strengthen the argument for the exclusion of all other pollutants as is currently the case under the standard method. Of course, it could still be argued that the EF leaves out many important environmental pressures but at least it would be consistent in doing so and arguing for the need for other indicators to be used alongside EF to cover all – or as close to all as possible – aspects of environmental pressures might seem even more reasonable.

Critics have also cast doubt on the method's reliability due to the fact that global EF for all land types other than CF have not changed much in the past half a century or so – the time span GFN's NFAs cover (Blomqvist et al, 2013; Blomqvist et al, 2013b; Giampietro and Saltelli, 2014) as explained in chapter 2. In addition, if CF is excluded from the accounts EF would not show any overshot globally. This might change the message associated with the method drastically. Humans would now be living within the limits of sustainability. Such a message is not in line with many other indications coming out of academia (Rockstrom et al, 2009; Barnosky et al, 2012). Part of the explanation lies in the fact the EF method is unable to detect unsustainable use of cropland, grazing land and built-up land. Rees and Wackernagel, 2013 (p.2) claim that this is how the calculations are "…*currently measured*…" (their emphasis), indicating that with further development this problem will be resolved when globally consistent data on land and ecosystem degradation becomes available.

This reliance on international databases is considered problematic by this thesis. It is argued that international databases are not robust enough to deliver reliable data for calculations as sensitive as EF and calls for the use of local data. Using local researchers with first-hand knowledge of their natural environment as well as economic and social condition would further decrease the risk of obvious errors going unnoticed. Perhaps those kinds of local EF accounts could include an assessment on the state of the land types in question, possibly under a pre-set criteria in line with suggestions from Lenzen and Murray, 2001 and Bastionini, 2012. A counter argument here would be that this is another reason for why CF needs to be included in the accounts, since, as Goldfinger et al, 2014 point out, the increased agricultural productivity goes hand in hand with increased CO_2 emissions. In this way, that is where the impacts show up – in a growing CF.

5.3.3 EF's ambition

Many of EF's limitations have been dealt with above, such as inability to distinguish between sustainable and unsustainable land use and limited coverage of environmental pressures. EF proponents have repeatedly pointed out that EF is being asked to perform tasks that it is not intended to do (Lin et al, 2015; Goldfinger et al, 2014) and is only intended to measure one aspect of sustainability[7] – *"…how much biocapacity humans demand in comparison to how much is available…*" (Lin et al, 2015 p.466). Although this thesis finds that the accounts have been in rapid development in recent years, critics have argued that GFN adamantly refuses to take note of criticism and make any substantial changes to the method (van den Bergh and Grazi, 2015). Another – and contradicting - critical point of view states that it is impossible to define the method since it is constantly changing in response to criticism (Giampietro and Saltelli, 2014). Likely, it won't be easy for GFN to satisfactorily respond to these opposing views!

Possibly, the plans for the EF were too ambitious from early on. It seems that the intention was to replace GDP as a standard measure for national progress – or use EF alongside it. Further, attempts were made to create a way to use EF to measure impact on a variety of scales – global, national, regional, city/municipal, product, service and individual levels were all expected to fall under the EF's domain. This lack of limits in the projects ambition may not have served it and possibly both diffused the energy and focus of the work as well as cause confusion as to what the EF is. One size fit all products invariably fit very few well in the end. Having said that, GFN's focus has mainly been on the NFAs of late.

5.4 The way forward for EF

According to this thesis, EF's problems may be summed up as follows: EF calculations are highly sensitive with a single datapoint being able to radically change results. Many inaccurate datapoints make an account very hard to interpret if not impossible. In light of this sensitivity, international databanks are not found to be robust enough to be usable for the accounts. Lack of knowledge of various natural systems and processes further limits accuracy, such as in MF and CF. It is further suggested that calculating global accounts or working across long distances with the calculations is likely to involve added uncertainty due to researchers lacking hands on knowledge of the system they are working with and therefore they cannot easily identify otherwise obvious errors in data. Caveats regarding uncertainty are often missing in dissemination of EF results, an issue of great importance that needs to be rectified.

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[7] Insufficient data has also been mentioned for leaving out various environmental pressures (Wackernagel and Silverstein, 2000). The two are of course not mutually exclusive.

This thesis thus indicates, that in order to strengthen the EF accounts, the following might be worth considering:

1. *Separate GFN outreach from the development of EF*

This thesis argues that the science of EF suffers from GFN being both the world's leading research institute focusing on the method as well as an NGO/think tank, dedicated to environmental activism. An important step forward in the development of EF would be to separate these two activities – useful as they both may be in separation, when combined, odds are the science suffers as reasoned in paper III.

2. *Drop calculations of CF from the standard method*

Currently data for CF calculations are so reliant on estimates and averages that results must inevitably be highly suspect. CF is further the most contested aspect of the EF method and has been severely criticised on several accounts (van den Bergh and Grazi, 2013; van den Bergh and Grazi, 2014; van den Bergh and Grazi, 2015; Blomqvist et al, 2013; Giampietro and Saltelli, 2014; Giampietro and Saltelli, 2014b), including for being hypothetical, arbitrary, using implicit weights and for the assumptions underlying it (van den Bergh and Grazi, 2013; van den Bergh and Grazi, 2014; van den Bergh and Grazi, 2015), for extremely sensitive calculations and uncertainty in measurements (Blomqvist et al, 2013) and for being the sole variable responsible for humanity's global overshoot (Giampietro and Saltelli, 2014b). Dropping CF from the accounts would thus resolve the most contested issue regarding the methodology. It could also be argued that dropping CF from the accounts would make the method more internally coherent as it would then be solely focused on resource depletion as opposed to covering resource depletion and one form of pollution – that of CO_2. This in turn would discount another frequent criticism on the method, that of it only taking into account one pollutant – CO_2 – and leaving out many other highly relevant ones.

3. *Efforts should be made to eliminate use of estimates and averages from the accounts, wherever possible*

In light of the great sensitivity of the accounts, efforts should be made to restrict the use of estimates and averages as much as possible. Since CF calculations are largely based on estimates and averages, dropping CF from the accounts is a good first step in this direction. Other efforts with this aim could be focused on further research into areas lacking information such as on trophic level and discount rate for MF calculations.

4. *Relevant caveats should always be used and mandated under the standard method*

EF accounts will invariably always include a level of uncertainty. This uncertainty should be made explicit at all times. Making such caveats a part of the standards of the standard method would be a good reminder for researchers to include uncertainty estimates and declarations.

5. *Take the focus of global measurements and put onto local ones*

This thesis doubts the robustness of international databanks for EF calculations. Researchers should be encouraged to focus efforts on data collection from local authorities and stakeholders. EF could in this manner be made more robust and trustworthy by attempting to produce a reliable template for local researchers to apply to their circumstances – with the proviso that accounts can never be more accurate than the input data used.

6. *Consideration could be given to separating aggregated results and disaggregated results*

As pointed out in the literature (Giljum et al, 2007; van Vuuren and Smeets, 2000) single figure results are helpful in dissemination of an ideology and starting conversations but distract from analytical soundness. Thus, for sake of accuracy and scientific endeavour for any kind of serious use of EF, disaggregation should be mandated (under the standard method), with single digit results being reserved for general public outreach purposes.

These steps would go a long way towards a more robust EF.

The thesis further suggests that uncertainty within cropland, grazing land, forests and built-up land is explored in a similar manner to what is done here. This thesis has shown the importance of data accuracy in EF calculations, with an emphasis on MF and CF as the most sensitive areas. Other land types of the EF have their own set of issues and should be studied in the same manner.

5.5 A few final words on EF and indicator use in policy making

A more robust EF, such as described above, would naturally have a higher utility for policy making – and as mentioned earlier, indicators are often closely linked to policy making – one could even argue it is their *raison d'être*.

Assessing the impact of EF on policy is not easy and would be a worthy task for a separate study. It should be clear though from this thesis that any use of EF for policy purposes needs to be approached with great care and deep scrutiny of results. EF proponents have for some years now recommended using EF in conjunction with other measures and this seems like a good idea for any indicator used for policy purposes. As indicated by this thesis, the uncertainty involved with EF calculations – as they currently stand under the standard method – makes it hard to speak in absolute terms regarding the results and therefore the same goes for any policy recommendation thereof. The same is likely to hold for any indicator relying on global datasets.

Given these problems, what is the way forward in using EF (and possibly, by extension, other sustainability indicators) in policy making? Data is, as we have seen in this thesis, such a crucial underlying factor, that the utility of any indicator can only be as high as the quality of the data. This thesis shows the value of using local data or any other data of most reliability. Further, large indicators, combining a wide range of variables and even fusing them together in a composite indicator such as EF, are likely to expound errors and inaccuracies. This points towards a future of specific indicators, used for isolated localized problems, measured and calculated by local researchers, using verifiable data. This, as opposed to the global scale all-encompassing indicator, calculated by a researcher who has never even visited the lion share of the areas he is assessing, may be a key to more robust sustainability indicators with higher utility for effective policy making. The downside on the other hand might be that they may not be as eye catching (and fund worthy?) – as the highly metaphoric, global scale indicators, predicting eternal doom for earth and mankind – which is always guaranteed to grab the headlines.

6 Conclusion

This thesis has attempted to answer the research question:

What can Iceland, as an outlier in EF standard method accounts, teach us about the uncertainty involved with the calculations?

The thesis only partly answers the research question, since a thorough deep dive was only undertaken with MF and CF, the hotspots for uncertainty within the Icelandic accounts. Regardless, it has demonstrated how EF standard method calculations are prone to high levels of uncertainty. The reasons for these uncertainties were identified as threefold:

- Discrepancy between local and international data sources
- Lack of knowledge of natural systems and processes
    - Which results in data gaps
    - Or leads to use of estimates
- Aggregation and use of averages

This uncertainty can lead to very seriously distorted outcomes, and hence, misleading results and conclusions. This makes EF vulnerable to all manner of misuse and abuse – such as for political or even financial gain. It is therefore of the utmost importance that uncertainty levels are always included in dissemination of EF results.

The findings of the dissertation show that using local data as opposed to global datasets can yield major improvements to the accuracy of the accounts. This points to a possible whole new direction for GFN as an institution where their role could be changed from creating annual global accounts (NFA), to an advisory role to local researchers working with local data and their local knowledge of environmental, and other relevant, factors.

It is suggested that the fact that GFN has been both the leading research institution for EF as well as engaging in free market operations, with EF as their product, may be a major hindering factor for further development of the method – and as such a leading cause for the backlash EF has encountered from some academics. A good example of this clash between the scientific and marketing ambitions of GFN, is the idea of dropping CF from the accounts – an idea endorsed by this thesis. This idea is not new but has always been spurned by GFN. This thesis puts forth a variety of reasons for why dropping CF would strengthen EF, but, at the same time, it will clearly cause all manner of problems for the outreach/free market activities of GFN and is thus likely to continue to be spurned while the two activities are under the same umbrella. Similarities are also drawn between GFN, the IPCC and the WHO in respect to this kind of mixing science with politics and doubts cast on any institution's ability to engage in the two without compromising the science. In addition to the compromised science, combining the two may be a factor in, what seems like, a rise in "scientific authoritarianism".

The dissertation further finds that EF's use of metaphor is not only a legitimate scientific approach but may be a key to its popularity and widespread use. It could be argued that

EF's metaphoric use has played an instrumental role in bringing the idea of "humans living within the means of earth's reproductive capabilities" to the public. This would make EF's utility enormous – possibly even regardless of its contested accuracy of results, as dealt with by this thesis. This highly effective use of metaphor is thus an important lesson that EF has to teach future makers of indicators and possibly other tools of ecological economics intended to capture the minds of the public.

In light of all this the following recommendations are suggested to strengthen future EF accounts:

1. Separate GFN outreach from the development of EF
2. Drop calculations of CF from the standard method
3. Efforts should be made to eliminate use of estimates and averages from the accounts, wherever possible
4. Relevant caveats should always be used and mandated under the standard method
5. Take the focus of global measurements and put onto local ones
6. Consideration could be given to separating aggregated results and disaggregated results

Following these recommendation would undoubtedly considerably decrease the uncertainty involved with the EF SM accounts and would go a long way towards bringing the two factions of proponents and critics of EF together.

EF has, arguably, something special that ignites people's imagination and as such is a rare and a precious thing. It has the potential of being an important educational tool and possibly even a useful part of a policy makers toolbox. In order for EF to fulfil that potential it is of vital importance that uncertainty levels with the calculations are brought down by any means possible.

History will decide if EF will be remembered solely as the innovator of ecological economics – the one that broke ground with introducing the ideas of human life in harmony with nature to the public – or if it will be one of its greats – that continued to grow as the knowledge base grew, both within academic, and public, spheres.

History – along with GFN, EF proponents, critics and users – will decide.

It will be an interesting story to follow.

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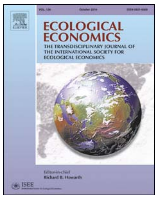

Analysis

Standard Ecological Footprint Method for Small, Highly Specialized Economies[☆]

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ABSTRACT

The negative impact of human endeavour on the biosphere has becoming increasingly clear in recent decades. This has spurred a surge in the creation of sustainability indicators. One of the most used sustainability indicators of recent years is the Ecological Footprint (EF). The EF uses trade flows to estimate environmental impacts of consumption. The purpose of this study was to test EF's ability to deal with a small but highly specialized economy. For this we used Iceland as a case study but the Icelandic economy is dominated by strong specialization, with fisheries dwarfing all other sectors. Global Footprint Network's standard methodology was utilized with only the addition of local data being used where these data proved more robust than international databases. The results from the two editions of the GFN calculation models, 2008 and 2014, yielded a footprint of 56.59 and 25.26 gha, per capita, respectively, for Iceland. Three main reasons were identified for the drop in the footprint between the two editions, all within the fishing grounds footprint: A much improved coverage of extraction rates, changes in fish species trophic levels and changes to aggregate errors for traded cod and halibut. A correction of CO_2 intensities for exports also had a big impact but resulted in a rise in the EF for the latter edition. The study highlighted the rapid development of the methodology as a major strength while the method's main weakness was revealed as the uncertainties associated with the marine footprint. Local consumption figures from the Icelandic Directorate of Health indicated that a further drop in the marine footprint is in store with increased accuracy of the method, mainly to do with accurate allocation between export and consumption footprints. Although the indicator's accuracy has been much improved in recent years, additional improvements are thus still needed. The extremes of the Icelandic economy highlight errors to the extent that the huge footprint the calculations yielded make the country an outlier in a global context. The indicator seems in this respect not accurate enough yet to be able to deal with such a degree of specialization, especially where the main sectors are very large in relation to the population – at least not when the sector in question is the marine sector. The upside of this is that highly specialized economies may in this way be very useful for identifying and correcting inaccuracies within the methodology for their sector of specialization.

1. Introduction

The negative impact of human endeavour on the biosphere has becoming increasingly clear in recent decades (IPCC, 2013; Kubiszewski et al., 2013; Niccolucci et al., 2012; Barnosky et al., 2012; Rockström et al., 2009; Turner, 2008; MEA, 2005). In response, the concept of sustainability - or sustainable development - has been getting ever more attention. The call for humanity to live within the means of nature's capability to provide goods and services has arguably never been louder. Since the United Nations Conference on the Human Environment in Stockholm in 1972, often considered the starting point of modern political and public environmental concern (Baylis and Smith, 2005), the concept has been bouncing around in ecological debate, being both argued for, and against, by environmentalists. Various definitions of sustainable development saw the light of day, but the most famous and most quoted today must be the Brundtland report (Our Common Future, WCED, 1987) definition:

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> "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Since the publication of the report and then the United Nations Conference on Environment and Development (UNCED) in 1992, the sustainability concept has become the centre of environmental debate (Feitelson, 1998) and great efforts have been put into the implementation of the concept (or aspects thereof) into global, national and regional policy through international environmental agreements (e.g. the Kyoto protocol, the Aarhus convention, the Paris agreement, etc.), national environmental policy plans (i.e. in the Netherlands, UK, Canada, etc.) and attempted implementation of Agenda 21, the UNCED 92's action plan aimed at achieving sustainability. Sustainability has thus been incorporated into the agenda of most governments worldwide (Rametsteiner et al., 2011).

1.1. Sustainability Indicators

It is clear that in order for sustainability to be anything more than a fancy word, ways to measure sustainability and progress towards it are needed. For this purpose, sustainability indicators are used. In Agenda 21 plans were made to develop sustainability indicators to form a basis for decision making (UNCED, 1992). This spurred a surge in sustainability indicator creation and development, resulting in a variety of indicators, measuring and monitoring a multitude of different variables. The role of these indicators has been defined by Ott (1978) as a way to:

> "…reduce large quantity of data to its simplest form, retaining essential meaning for the questions that are being asked."

McGlade's (2007) definition is for the most part in agreement, although she adds the necessity of being relevant for policy-making and easily understood by the public:

> "The main purpose of any sustainability indicator framework is to provide a comprehensive and highly scalable information-driven architecture that is policy relevant and understandable to members of society and will help people decide what to do."

The United Nations echo this in their *Guidelines and Methodologies for Indicators of Sustainable Development* (2007):

> "Indicators perform many functions. They can lead to better decisions and more effective actions by simplifying, clarifying and making aggregated information available to policy makers. They can help incorporate physical and social science knowledge into decision making, and they can help measure and calibrate progress toward sustainable development goals. They can provide an early warning to prevent economic, social and environmental setbacks. They are also useful tools to communicate ideas, thoughts and values."

Sustainability indicators can now be counted in their hundreds (Singh et al., 2009),of varying sizes and scopes, all aimed at quantifying the human impact on the natural resource base, or aspects thereof, and helping to define a "safe zone" for humanity to operate in. Examples of these are: Index of Sustainable Economic Welfare (ISEW), Measure of Economic Welfare (MEW – precurser of ISEW), Genuine Progress Indicator (GPI), Dashboard of Sustainability (DS), City Development Index, emergy/exergy, System of Economic Environmental Accounting (SEEA), Human Development Index (HDI), Life Cycle Analysis (LCA), Sustainable National Income (SNI), Environmental Net National Product (ENNP), Environmental Policy Index (EPI), Living Planet Index (LPI), Material Flow Analysis (MFA), Environmentally-adjusted Domestic Product (EDP), Genuine Saving (GS), Environmental Vulnerability Index, Environmental Performance Index, Ecological Footprint and The Physical Quality of Life Index (PQLI), to name but a few. It is outside the scope of this paper to make any comparison between these indicators/indices but such comparisons can be found in, e.g., Böhringer and Jochem, 2007; Mori and Christodoulou, 2012; Olafsson et al., 2014; Singh et al., 2009). The only indicator we will focus on here is the Ecological Footprint (EF) (Rees and Wackernagel, 2004; Wackernagel and Rees, 1996; Wackernagel et al., 2002).

1.2. Ecological Footprint

Since its conception EF has enjoyed considerable popularity, with professionals and laymen alike, and according to Binningsbo et al. (2007) it has in recent years become the most widely used sustainability indicator in the world. Although EF has been used to estimate sustainability at various levels – product (Limnios et al., 2009; Frey et al., 2006), business (Bagliani and Martini, 2012), sectoral (Kissinger, 2013; Herva et al., 2008), municipal (Cano-Orellana and Delgado-Cabeza, 2015; Scotti et al., 2009), regional (Cui et al., 2004; McDonald and Patterson, 2004), etc. – its most common use is on a national level (Salvo et al., 2015; Galli et al., 2012; Wang et al., 2012; Medved, 2006; Haberl et al., 2001). The Global Footprint Network (GFN), an NGO whose principal aim is furthering and spreading the methodology, furthermore calculates every year the EF for over 200 countries in what they call the National Footprint Accounts (NFA) (footprintnetwork.org, 2017). The EF sets itself aside from many sustainability indicators by focusing on primary production. The EF attempts to assess sustainability by asking two questions: How much primary production takes place on Earth in any given year and how much of that production is being consumed by humans? If the consumption is less than the production the EF assumes the population under investigation is living sustainably. If the population is consuming more than earth is producing a state of "overshot" is reached – i.e. the population is not living sustainably.

In the GFN publication The Ecological Footprint Atlas 2008 (Ewing et al., 2008) it is stated that results for countries with populations counting less than one million people are not reported in the National Footprint Accounts since "…smaller economies are more prone to distortion". No further explanation is given for this inability of the indicator to deal with smaller economies. Older GFN publications of the NFA thus only include nations with populations over one million. Smaller nations are not included due their data being less reliable and more prone to distortion (Ewing et al., 2008). In the latest version of the NFA this is no longer the case and nations as small as Nauru, the world's least populated country after Vatican city, with its population of 10,301 (worldometers.info, 2017), is presented and so is the British overseas territory of Montserrat, with a population of 5179 (worldometers.info, 2017).With this GFN no longer disqualifies countries due to the size of the population but rather the emphasis is now on data quality, and only those countries whose data quality meet the quality standards of GFN are included in the accounts (footprintnetwork.org, 2017).

Iceland is one of the countries not included in the NFA. With a population of 338,349 in 2017 (hagstofa.is, 2017) Iceland is certainly larger in terms of population than many of the countries that are included. Personal communication with GFN reveals that when putting together a new edition of the NFA the researchers.

"…assess a level of confidence in the final results for each country." (Global Footprint Network, 2017).

By way of deduction this must mean that confidence in the results for Iceland are not high enough for the country to be included in the accounts. This is surprising, since the country has a well-developed infrastructure and comprehensive data collection systems, with the Icelandic statistics office Statistics Iceland being a part of the European Statistical System. A possible explanation may be found in the size of the country's trade flows in relation to its economy, but this can be a source of bias because - according to the Ecological Footprint Atlas 2009 - the resources used and the waste generated in making exported goods are not fully documented (Ewing et al., 2009). Again, this is not explained any further.

Iceland's trade flows are certainly large in relation to the economy.

The most outstanding feature is export of fish produce, but even with a population this small the country counts as the ninth largest fish exporter in Europe (worldrichestcountries.com, 2017). Other specific features affecting trade flows are electricity and heat production dominated by nearly zero-carbon hydro- and geothermal energy generation, which has attracted aluminium producers to the country, making aluminium Iceland's main export after fish, as well as a cold northern climate that restricts agricultural production and makes the country reliant on imports for most daily necessities.

This paper follows up on a study prepared at the University of Iceland (Jóhannesson, 2010) where the main findings, although inconclusive, were the, seemingly, great size of Iceland's EF (56 gha). Since Iceland is not included in the NFA the only other published figure for the Icelandic footprint can be found in Wackernagel et al., 1999 (7.4 gha). At the time this study was being carried out (1997 – data year 1993) the international databanks used suffered from wide gaps in Icelandic data. Furthermore, this study was an early attempt at including the sea in the calculations but did not state explicitly the method used to calculate the marine footprint. It is therefore not entirely clear how sophisticated this initial marine footprint calculation method was. This only published study on Iceland's EF thus seems not only highly inaccurate due to lack of data but is also likely to be outdated in terms of methodology. The study from the University of Iceland supports this suggestion by showing a considerably larger footprint for the Icelandic economy (both with- and without the sea) than the 1999 study yielded. The need for an updated study is therefore clear.

We argue that in order to be considered a universally applicable metric, an indicator such as the EF should be able to deal with any economy, regardless of population size or the size of its trade flows, given adequate data availability. If anything, a small and highly specialized country like Iceland should present an interesting case to test the robustness of the indicator as the economy has specific features sustainability indicators of this kind need to be able to account for. The country's isolation, its well-developed infrastructure and relatively comprehensive data collection should also increase the accuracy of the data, making the country even more suited to testing the methodology and possibly highlighting its flaws. In light of this we argue that there is a clear need for an updated study on the EF of Iceland, which makes use of the comprehensive data collection in the country. We further argue that the way the indicator manages to deal with the specific features of the Icelandic economy, especially in relation to fisheries and energy production, will highlight either strengths or weaknesses of the method – and may reveal why it is not yielding realistic figures for the Icelandic economy – if that is the case.

1.3. *Aim of this Study*

The aim of this project was to measure the Ecological Footprint of Iceland, using the standard methodology as published by the GFN, and to analyse the potential sources of errors and biases of the method when applied in such a context as provided by a small and specialized economy like Iceland. The only change to the standard methodology implemented was the use of local databases wherever possible, as suggested by Kitzes et al. (2009). A comparison of the data from the international datasets used for the 1999 Wackernagel study to local datasets for the same time also proved favourable to the local ones.

To get a clear picture of methodological changes in recent years 2005 data were input into two editions, 2008 and 2014, of GFN's standard methodology model. The 2008 edition yielded a footprint of 56.59 gha and the 2014 edition of 25.26 gha. According to the 2008 edition no country in the world had a double-digit footprint in 2005, with United Arab Emirates having the largest footprint in the world of 9.46 gha and the USA with 9.42 gha. Countries with population sizes under one million were not included. The country closest to Iceland in population size included in the 2017 accounts was Barbados, population 285,744 (worldometers.info, 2017) with a footprint of 3.36 gha, French overseas regions of French Polynesia, population 288,685 (worldometers.info, 2017) with a 4.04 gha footprint, and Martinique, population 396,071 (worldometers.info, 2017), with a 4.51 gha footprint.

For Iceland the land types of carbon and fisheries were the factors responsible for the sizeable footprint and the Icelandic case indeed highlighted some serious issues with the methodology. The 2014 edition had corrected the major issue with the Icelandic carbon calculations from the 2008 edition, leaving the marine component as the remaining problem area. We conclude that it is not so much the size of the economy that makes the calculations prone to distortion but its specialization, and the ratio between the size of the population and the size of the given sector within the economy will magnify any associated errors. The fragility of the marine component calculations is well known and is clearly stated in the NFA guidebooks, but the Icelandic case brings to light how serious these can become when there is a high degree of specialization within the economy.

In the following section we will briefly go through the methodology of the EF; Section 3 explains the design and progression of the study, Section 4 reveals the results, Section 5 discusses the main findings and methodological questions highlighted by the study, and Section 6 concludes the paper with a few final remarks.

2. Method: Ecological Footprint of a Nation[1]

The standard methodology of calculating the Ecological Footprint of nations has been extensively covered in the literature, from the more simplified early works of Wackernagel and Rees (1996) and Rees and Wackernagel (1996), through the various alterations and modifications highlighted in, e.g., Wackernagel et al., 2002; Monfreda et al., 2004; Kitzes et al., 2007 and Ewing et al., 2010 to the latest version of the standard methodology coming out of the GFN think tank in Boroucke et al., 2013. For readers unfamiliar with the approach a brief summary of the key components of the methodology is provided below but more detailed descriptions can be found in the literature, such as in Monfreda et al., 2004 and the semi-standardized updates of the following years such as Wackernagel et al., 2005; Kitzes et al., 2006; Ewing et al., 2008, Ewing et al., 2010 and Borucke et al., 2013. The summary below is largely based on these papers and follows a similar structural framework.

The Ecological Footprint aims to measure nature's regenerative ability and weigh that up against human resource requirements. To do this it attempts to measure annual primary production in the area under investigation – referred to as biocapacity - and pitch that against the total primary production required for the consumption of its human inhabitants – referred to as the Ecological Footprint. In the words of one of the method's main authors, Wackernagel et al. (1999), from an early work:

> "…ecological footprints show us how much nature nations use."[2]

The idea here is that all human consumption can be traced to the relevant land/landscape type (including sea and water) providing the natural resources needed to produce the goods and services being consumed (Wackernagel et al., 2002). The methodology defines six land types for this purpose: Cropland, grazing land, forests, sea and water, built-up land and carbon uptake land. Measuring of built-up land aims to estimate the primary production capacity lost under human infrastructure such as buildings, roads, reservoirs, golf courses, etc., and carbon uptake land represents the size of the forest area needed to sequester anthropocentric CO_2 emissions of the population in question.

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[1] Since the methodology for Ecological Footprint calculations differs depending on the unit under investigation, what follows applies to calculations for national EF and biocapacity, as this was the relevant method for this study.

[2] Although this definition applies to national consumption, it could just as well be applied to any other defined group of people, as shown in the introduction above.

The Ecological Footprint, and its biocapacity counterpoint, is represented by a normalized unit called global hectares (gha). In order to convert the size of the areas into this unit, two co-efficients are utilized to account for the difference in productivity between the land types – equivalence factor (EQF) – as well as the difference in productivity between the same land types in different countries – yield factor (YF).

The general calculation for the footprint then utilizes these two coefficients to normalize the ratio of production/consumption (P) and the national yield (Y_N) for the product in question as

$$EF = \frac{P}{Y_N} * YF * EQF$$

For land types yielding only one product (all except cropland, according to the standard method) this becomes

$$EF = \frac{P}{Y_W} * EQF$$

Additional calculations using this basic equation may then be needed to estimate the production/consumption or yield where data are lacking.

Calculations for fisheries yields are based on the primary production requirements (PPR) to sustain the harvest

$$PPR = CC * DR * \left(\frac{1}{TE}\right)^{(TL-1)}$$

where CC is the carbon content of the wet-weight of the fish, DR is a constant discount rate, assumed to be 1.27 for all fish species, TE is the transfer efficiency between trophic levels, and TL is the species trophic level. This approach is based on the work of Pauly and Christensen (1995) and the equation was used to calculate the primary production requirements for 19 species of fish, for which Gulland (1971) estimated the annual sustainable harvest. The sum of these is the assumed marine primary production sustainably harvestable. The global average yield for fisheries (Y_M) is therefore given as

$$Y_M = \frac{PP_S}{A_{CS}}$$

where PP_S is the global sustainable harvest and A_{CS} is the global continental shelf area.[3]

Once the production footprint is known for all land types, import/export footprints are calculated using the same methods. Import footprints are then added to the production footprints and the exports then subtracted. These consumption footprints are then added up to form the final Ecological Footprint. Biocapacity (BC) for each land type is found by

$$BC = \sum_{1} A_{N,i} * YF_{N,i} * EQF_{N,i}$$

where A is the area available for the production of product i and$YF_{N,\ i}$ and $EQF_{N,\ i}$ are the yield and equivalance factors for the land type producing the product i.

Products that are made from primary products, so-called derived or secondary products, don't normally share the yield of the primary product, since the production, in most cases, reduces the yield of the secondary product. Because of this, yields for derived products need to be calculated before the footprint can be determined. To do that extraction rates, that are the ratio between the yields of the primary and secondary products, are multiplied with world average yields of the primary product

$$Y_{W,D} = Y_{W,P} * EXTR_D$$

where $Y_{W,\ D}$ and $Y_{W,\ P}$ are the world average yield for the derived and primary products, respectively, and $EXTR_D$ is the extraction rate for the derived product. Where the primary product yields more than one derived product simultaneously a footprint allocation factor (FAF_D) is needed to allocate the footprint to the derived products without double counting;

$$EXTR_D = \frac{TCF_D}{FAF_D}$$

TCF_D here is the technical conversion factor that depicts the ratio between the primary product input and the derived product yield in mass units. The FAF_D is found by

$$FAF_D = \frac{TFC_D * V_D}{\sum TFC_i * V_i}$$

where the TCF-weighted prices (V) for the derived products are used to allocate the footprint between all the simultaneously produced products' prices (V_i).

Although the method has received its fair share of criticism (Giampietro & Saltelli, 2014a and b; Fiala, 2008; Ferng, 2002; Ayres, 2000; Moffatt, 2000; van der Bergh and Verbruggen, 1999; Ayres) it is worth keeping in mind what it is intended to do and then by definition, what not. As Borucke et al. (2013) put it:

> "The National Footprint Accounts measure one main aspect of sustainability only – *how much biocapacity humans demand in comparison to how much is available* – not all aspects of sustainability, nor all environmental concerns."

There are many human activities and consequences that are not captured by this definition. Pollution from heavy metals, persistent organic pollutants (PCBs, CFCs, etc.) and radioactive materials are some of the things that fall completely outside of the calculations of the footprint. Water use, resource degradation and the social and economic dimensions of sustainability are also big issues that fall outside the metric's scope (Kitzes and Wackernagel, 2009).

Since the method is totally dependent on robust data for the accounts, a major limiting factor in being able to justly portray "…how much biocapacity humans demand…" (Borucke et al., 2013) is having accurate data for all human consumption and the waste that it produces. Unfortunately, this is rarely the case, especially when it comes to waste flows. GFN maintains that the only waste product with robust enough datasets for the footprint accounts is carbon dioxide and therefore it could be said that the Ecological Footprint only portrays a part of the real ecological footprint humans leave behind (Ewing et al., 2008). Hence data availability is a major limiting factor for footprint accounts.

In the Working Guidebook to NFA 2014 - a handbook of sorts, published by GFN for users of the accounts - Lazarus et al. (2014) warn against high sensitivity in fish yield calculations, especially in relation to trophic levels. Uncertainties in these calculations must be considered a serious limitation to the methodology in its present state. Changes to these calculations, such as suggested in a recent article by Luong et al. (2015), hold a promise for improvements in the EF methodology.

Critics of the EF have frequently raised questions about the carbon footprint calculations (Giampietro and Saltelli, 2014; Blomqvist et al., 2013; van den Bergh and Grazi, 2014; van der Bergh and Verbruggen, 1999) and various different methods of calculating the carbon footprint have been suggested and discussed (Kitzes et al., 2009). In spite of this, no major changes have been made to the carbon footprint method calculations in recent years but deeper explanations have been offered (Mancini et al., 2016) and criticism met with counter arguments (Galli et al., 2016; Goldfinger, 2014; Rees and Wackernagel, 2013).

Thorough discussions on the EF limitations can be found in the literature, such as Galli et al., 2011, Ewing et al., 2010, Kitzes et al., 2009 and Monfreda et al., 2004. One aim of this study was to look at the high uncertainty contained in the marine component and thereby contribute to the development of EF methodology. Hence we will return to the uncertainty issues in the discussion section of this paper.

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[3] Only fishing taking place on the continental shelf areas is included as it is assumed 95% of all fishing takes place there (Kitzes et al., 2007).

Table 1
EF and biocapacity of Iceland, per capita, 2008 edition results.

Land type	Production	Imports	Exports	Consumption	Biocapacity
[−]	[gha]	[gha]	[gha]	[gha]	[gha]
Cropland	0.07	0.51	0.02	0.56	0.02
Grazing land	0.46	0.00	0.02	0.44	0.46
Forest	0.00	0.54	0.00	0.54	0.03
Fisheries	62.67	1.32	9.38	54.61	17.32
CO_2 uptake l.	2.77	8.71	13.19	0.00	0.00
Built up land	0.44	–	–	0.44	
Total	66.40	11.09	22.60	56.59	18.26

The methodology for national footprint accounting is described in detail in relevant material from Global Footprint Network and in the literature (Borucke et al., 2013; Ewing et al., 2010; Ewing et al., 2008; Monfreda et al., 2004).

3. Research Design

The purpose of this study was to measure the ecological footprint of Iceland according to the latest methodology as stated in official GFN documents such as the *Working Guidebook to the National Footprint Accounts: 2014 Edition* (Lazarus et al., 2014), *Calculation Methodology for the National Footprint Accounts, 2008 Edition* (Ewing et al., 2010), *Guidebook to the National Footprint Accounts: 2008 Edition* (Kitzes et al., 2008) and the *Ecological Footprint Atlas 2010* (Ewing et al., 2010). In order to get the most accurate outcome a decision was made to use local databases, rather than the suggested international ones, wherever they proved more detailed. This was the only way the study did not follow the traditional method as indicated by GFN but completely in line with its standards of practice as set forth in the Ecological Footprint Standards 2009 (Global Footprint Network, 2009).[4] We utilized two editions, 2008 and 2014, of the Learning License Workbook, available at the GFN website, free of charge, as a basis for the calculations.

The data used for the study were for the year 2005.[5] International databases were utilized in conjunction with local ones for data on the size of the Icelandic continental shelf (World Resource Institute), production and trade in wood products (FAOSTAT (FAO ForesSTAT Statistical Database)) and the import and export of agricultural products (TradeSTAT (FAO TradeSTAT Statistical Database)). In all other cases local datasets were more detailed than international ones. The following local knowledge was therefore utilized for the study: Corine 2006 (Arnason and Matthiasson, 2009) of the National Land Survey of Iceland for sizes of the different land types, the Marine Research Institute (Gudmundsson and Valsdottir, 2004) for net primary production per square meter within Icelandic fishing grounds, Icelandic Forest Service for annual growth and estimated total production of Icelandic forests, National Energy Authority of Iceland for geothermal and hydro-powered electricity production, Statistics Iceland for total anthropocentric CO_2 emissions of Iceland, import-export figures, catch numbers for marine fisheries and total population and livestock sizes, The Farmers Association of Iceland for livestock sizes, crops and the share of cropland “rested” annually, the Icelandic Beekeeping Organization for the number of beehives, and the Institute of Freshwater Fisheries for catch numbers from freshwater fisheries.

4. Results

Both editions used, 2008 and 2014, yielded the world's largest footprint for the year 2005, yet with a considerable difference in total size. The 2008 edition resulted in a per capita footprint of 56.59 gha, while the 2014 edition gave a 25.26 gha result. Following is a more detailed breakdown of the results from the two editions. For the sake of clarity we will go through the results of the 2008 edition first and then show where the 2014 edition results differ.

4.1. Results from the 2008 Edition

The 2008 edition of the GFN calculation model calculates the footprint of Icelandic consumption in the year 2005 as 16,977,222 global hectares. The country's biocapacity calculations come to 5,478,252 gha. When we then divide this between the 300,000 (rounded number according to methodology) inhabitants, each Icelander is responsible – on average - for the consumption of what amounts to 56,59 global hectares per year. According to the NFA for the year 2005 the nations with the highest footprint were the United Arab Emirates and the United States of America with a footprint of 9.46 and 9.42 gha, respectively. Big fishing nations such as China, Myanmar and Norway had footprints of 2.11 gha, 1.11 and 6.92 gha respectively. The countries with the smallest populations presented in the accounts were Swaziland, with a population of 1.03 million (rounded number according to methodology), Mauritius, population 1.25 million and Trinidad and Tobago with a population of 1.33 million had footprints of 0.74 gha, 2.26 and 2.13 gha, respectively.

Table 1 shows the per capita footprint and biocapacity of Iceland, according to the 2008 edition model.

Of the six land types it is the fisheries that is the biggest and is in fact responsible for 97% of the total footprint. Of the 62.67 gha needed for the production of Icelandic fisheries only 9.38 is exported and therefore subtracted from the production and imports. This leaves a consumption footprint of 54.61 gha. The biocapacity of the Icelandic waters comes to 17.32 gha but since the marine footprint accounts for all fish landed within a country that may or may not be caught within its waters, the sustainability of a country's fisheries is never assessed by comparing its footprint to its biocapacity.

With no other country having a footprint amounting to a double-digit number in the year 2005, it seems clear that Iceland had by far the largest Ecological Footprint in the world in that year, assuming that the standard methodology is capable of producing reliable results. However, as the result was entirely due to the size of the fisheries component, the reliability should be analysed further. Looking at the sizes of the usable areas of the different land types (Table 2), the marine component stands out.

Table 2 shows how large the continental shelf area is in comparison to other areas used for production in Iceland. However, Icelandic fisheries do not limit themselves to the continental shelf area so the actual size of the area being used is even larger than shown here. This means that the calculations will show a lower biocapacity then they ought to. On the other hand the figure for national yield of the Icelandic marine land type used for the study is higher than the world average, as seen in Table 3 below.

The standard methodology uses data from www.seaaroundus.org for marine yields. According to www.seaaroundus.org, the net primary production (NPP) of Icelandic waters is 492 $\mathrm{mgC{\cdot}m^{-2}{\cdot}day^{-1}}$. In keeping with the aims of this study we used a figure from the Icelandic Marine Research Institute website of 597 $\mathrm{mgC{\cdot}m^{-2}{\cdot}day^{-1}}$. This results in a yield factor of 1.18 for the Icelandic fisheries. This gives us an outcome of higher biocapacity for the marine component than if the yield given by www.seaaroundus.org was used. Using the figures from seaaroundus.org would result in the biocapacity for the marine land type going from 17.32 down to 14.32 gha.

No figures can be shown for national and world yields for cropland in Table 3 since the land type provides many different products with varying yields. The yield factor therefore is dependent on an aggregate of the area sizes needed to grow crops nationally in relation to the world average area size needed for the same crops. Since infrastructure

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[4] See Standard A3: Use of Non-Conventional Elements in Footprint Analysis.

[5] A second study will utilize the latest available data, allowing for comparisons between years before and after the collapse of the Icelandic economy in 2008.

Table 2
Area sizes, Iceland, 2008 edition results.

Reference	Description	Land type	Size (ha)
CORINE2006	Arable l. and perm. crops	Cropland	2062
CORINE2006	Pastures and mosaics	Grazing land	250,244
CORINE2006	Forested land	Forest	31,373
CORINE2006	Other wooded land	Grazing land	30,100
CORINE2006	Rivers and lakes	Marine – rivers/lakes	204,150
WRI	Marine – cont. shelf	Marine – sea	10,868,300
CORINE2006	Artificial areas	Built-up land	39,600
CORINE2006	Reservoirs	Reservoirs	24,800

Table 3
Yield factors, Iceland, 2008 edition results.

Land type	National yield	World yield	Yield factor
[−]	[t nha^{-1}]	[t wha^{-1}]	[wha nha^{-1}]
Cropland	–	–	1.25
Grazing land	6.08	6.19	0.98
Marine	597	504	1.18
Inland water	–	–	1.00
Forest	0.45	2.36	0.19
Infrastructure	–	–	1.25

Table 4
Biocapacity, Iceland, 2008 edition results.

Land use type	Area	YF	EQF	BC
[−]	[nha]	[wha nha^{-1}]	[gha wha^{-1}]	[gha]
Cropland	2062	1.25	2.64	6830
Grazing land	250,244	0.98	0.50	122,001
Other wooded land	30,100	0.98	0.50	14,675
Forest	31,373	0.19	1.33	7911
Marine	10,868,300	1.18	0.40	5,114,496
Inland water	204,150	1.00	0.40	81,083
Infrastructure	39,600	1.25	2.64	131,166
Hydro	91	1.00	1.00	91

is assumed to grow on cropland this is also the reason no figures are shown for the national and world yields. Blanks in yields for rivers and lakes are due to a lack of data on freshwater ecosystems productivity (Borucke et al., 2013). Hence the land type is given a yield factor of 1.

An interesting finding of the yield factor calculations is how Icelandic cropland is producing more per square meter than the global average. An explanation for this can be found in the use of greenhouses, resulting in very high yields for common vegetables such as cucumbers and tomatoes. These above-average yield factors for cropland and the marine land types, coupled with a relatively large usable area – especially for the marine land type – and a small population, are responsible for the large per capita biocapacity for the country, as only Gabon and Canada had more biocapacity per capita in 2005, or 24.97 and 20.05 gha, respectively (Ewing et al., 2008) (Table 4).

The other most outstanding feature of the outcome, as shown in Table 1, is how carbon uptake land returns a negative result, leaving what amounts to no consumption in carbon uptake lands due to the large size of the export category, which then erases the production and imports categories. Table 5 shows the categories responsible for the largest carbon footprints (CF) for foreign trade.

Of exported goods, unwrought aluminium and aluminium alloys had the largest carbon footprint or 2,085,383 gha, followed by fish - fresh, chilled or frozen 859,652 gha and salted, dried or smoked 144,257 gha, meat & fish meal, unfit for human consumption 219,037 gha, and oils of fish and marine mammals 108,850 gha.

Table 5
Largest trade footprints, Iceland, 2008 edition results.

Name	CF imports	CF exports	I/E CF balance
[−]	[gha]	[gha]	[gha]
Fish, fresh, chilled or frozen	32,053	859,652	− 827,599
Fish, salted, dried or smoked	483	144,257	− 143,774
Crustacea & molluscs, fresh, chilled, salted, dried	104,763	8502	96,261
Fish, in airtight containers	968	51,706	− 50,738
Meat & fish meal, unfit for human consumption	2085	219,037	− 216,952
Petroleum, crude & partly refined	107,563	10,526	97,037
Oils of fish and marine mammals	4853	108,850	− 103,997
Aluminium and aluminium alloys, unwrought	8051	2,058,383	− 2.050,332
Aluminium and aluminium alloys, worked	88,586	561	88,025
Fin.structural parts & structures of iron, etc.	78,613	79	78,534
Electrical machinery and apparatus, nes	585,486	5005	580,481
Chassis with engs. Mntd. For vehicles of 732.	134,572	1251	133,321
Furniture	88,362	123	88,239

Of imports the largest share was taken up by electrical machinery and apparatus, nes[6] 585,486 gha, chassis with engines 134,572 gha, petroleum, crude & partly refined 107,563 gha, crustacea & molluscs 104,763 gha, and aluminium and aluminium alloys, worked 88,586 gha.

4.2. Deviations of the 2014 Edition Results from the 2008 Edition Results

The 2014 edition of the GFN EF calculation model shows the EF of Icelandic consumption for 2005 as 7,578,474 gha and a biocapacity of 5.445.380 gha. This breaks down to a footprint of 25.26 gha per person with biocapacity remaining very similar to the 2008 edition or 18.15 gha (Table 6).

Since the data used for the two editions were the same, all changes in the results stemmed from changes in methodology or improvements in calculations and data availability. No change occurred in the results of the forest calculations, but all other land types changed to some extent. Minor changes in the results for cropland, grazing land and built-up land had minimal impact on the Icelandic footprint and can largely be explained by the latter edition better managing to account for imports and exports and accounting for unharvested cropland.

The two major changes for the Icelandic case took place within fishing grounds and the carbon footprint. The EF of marine product production went from 62.67 gha to 63.16 and the imports from 1.32 gha to 5.59 but it was within the export and consumption categories that the major changes occurred. The export category went from 9.38 gha to 56.18 and the consumption from 54.61 gha down to 12.57. Biocapacity remained about the same at 17.31 gha.

Similarly, the changes in the production and import components of the carbon footprint are noticeable but not drastic. The production changed from 2.77 gha to 2.59 and the imports from 8.71 gha to 10.22. Again, it was in export and consumption where the big changes took place. The export category went from 13.19 gha down to 2.08 and consumption from 0 to 10.74 gha. This is a mirror image of what took place within the fisheries where the bulk of the production/import went from the consumption category to exports. Here the bulk of the production/import footprint moved from exports to consumption.

Looking at the changes in the EF of other countries between the two editions may help put the Icelandic results into some perspective, but it should be remembered that this study has only calculated the footprint

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[6] Not elsewhere specified.

Table 6
EF and biocapacity of Iceland, per capita, 2014 edition results.

Land type	Production	Imports	Exports	Consumption	Biocapacity
[−]	[gha]	[gha]	[gha]	[gha]	[gha]
Cropland	0.05	0.85	0.09	0.81	0.02
Grazing land	0.41	0.00	0.19	0.22	0.41
Forest	0.00	0.54	0.00	0.54	0.03
Fisheries	63.16	5.59	56.18	12.57	17.31
CO_2 uptake land	2.59	10.22	2.08	10.74	0.00
Built-up land	0.38	–	–	0.38	0.38
Total	66.59	17.20	58.54	25.26	18.15

Table 7
Per capita footprints of various countries, 2008 and 2014 editions.

Edition	2008	2014
[−]	[gha]	[gha]
UAE	9.46	7.75
USA	9.42	6.98
China	2.11	2.19
Myanmar	1.11	1.92
Russia	3.75	4.06
Chile	3	2.86
Peru	1.57	1.53
Swaziland	0.74	1.75
Trinidad & Tobago	2.13	7.40
Mauritius	2.26	4.36

of Iceland using the *same data* for two different editions of the accounts and therefore changes in results for other countries may have been due to differences in input data as well as changes in calculation methods or data. Table 7 shows the EFs of a select group of countries from the 2008 accounts and the 2014 accounts. The data used were for 2005 and 2010 (as opposed to 2005 only, as done here for Iceland). The countries with the largest footprints in the 2008 accounts, the UAE and USA, both saw a decrease in their footprint between the two accounts from 9.46 to 7.7 gha and 9.42 to 6.9 gha, respectively. The footprints for nations with big fisheries like China and Russia[7] changed minimally from 2.11 to 2 gha and 3.75 to 4.1 gha, respectively, while Myanmar experienced a rise from 1.11 to 1.8 gha. Heavy fishmeal and fish oil exporters such as Chile and Peru saw almost no change between the two editions, and Chile's footprint stayed the same while Peru's EF rose by 0.07 gha. The smallest nations accounted for in the two editions, Swaziland, Trinidad and Tobago and Mauritius, all with populations just over a million, all saw a rise in their footprint from 0.74 gha to 1.7 for Swaziland, 2.13 to 7.4 for Trinidad and Tobago, and 2.26 to 4.4 for Mauritius.

5. Potential Method Weakness and Uncertainty Analysis

The aim of this study was to calculate the Ecological Footprint of Iceland, and to analyse the suitability of the standard method, given the particular conditions of a small country with a high degree of industry specialization. The study was conducted following the guidelines given by the Global Footprint Network, with the only addition of using local databases wherever possible – or where they proved more detailed than the international ones utilized by the standard methodology. The two editions of the GFN calculation model used in the study to calculate the footprint of Icelandic consumption data for 2005 resulted in a footprint of 56.59 and 25.26 global hectares per capita, respectively, but serious potential sources of bias were detected as well.

According to the latest and most up-to-date NFA, the 2017 edition, no country has ever reached 20 gha per capita in any given year since 1961, or as far back as the data stretch. The highest figure found in the accounts is for Luxembourg for 2003 of 17.19 gha. The largest footprints outside Luxembourg are for Qatar in 2013 of 12,6 gha and Norway in 1971 of 11.59 gha.

The reasons for the large size of the Icelandic footprint lie first and foremost in the size of the marine footprint. The fisheries EF must be explained either with overfishing – as defined by the methodology – or by methodological or data issues, i.e. problems with the fisheries methodology or the data used (or not used in the case of data gaps, etc.) that lead to such a big footprint for Icelandic fisheries. We hypothesize the latter is mainly at play here.

Uncertainty in the marine footprint calculations has been dealt with to some extent in the literature. In the *Working Guidebook to the National Footprint Accounts 2014*, Lazarus et al. (2014) underline this uncertainty, especially in relation to large standard errors in trophic level estimates - a conclusion also reached by Parker and Tyedmers (2012) - and using one figure for the bycatch for all species. Kitzes et al. (2009) point out that bycatch figures are based on estimates for a single year rather than a time series, as well as echoing Pauly's own warnings about the limits of the method when it comes to errors due to estimation, data limitations and inaccurate reporting (Pauly, 1996; Watson and Pauly, 2001).

We will now look at the most obvious problems that arose with the marine calculations for the Icelandic case.

5.1. Issues with Marine Footprint Calculations

The results from the two calculations indicate that the models reveal the difficulty in allocating impacts correctly between the export and consumption categories of the marine footprint calculations. The 77% drop in the marine footprint between the two editions suggests that major improvements have taken place in this respect in the development of the models between the 2008 and 2014 editions. We identified three changes in the latter edition that explain this great difference between the two models:

- A much improved coverage of extraction rates
- Changes in trophic levels
- “Corrections” of aggregate errors

5.1.1. Improved coverage of extraction rates

Extraction rates are used in the EF calculations to estimate the yield of secondary goods and as such are vital to generate reliable figures for exports and imports. In the 2008 edition extraction rates for marine commodities were severely lacking. Most species utilized by the Icelandic fisheries were missing extraction rates and therefore no loss in yield was accounted for when the goods were shipped out of the country. This treatment overestimated the yield and therefore gives a smaller export footprint. A smaller export footprint then resulted in a larger overall footprint. For rendered products such as fishmeal and oils this means there were finally figures for the product yields that therefore could be entered into the calculations. These alone accounted for almost 16 gha.

In the 2014 edition all the commodities exported from Iceland were assigned extraction rates and therefore had substantially lower yields. That, and the inclusion of fishmeal and oils, led to a significant rise in the export footprint.

5.1.2. Changes in trophic levels

Considerable changes have been made to estimated trophic levels between the two editions and most of the exported products have associated species with raised trophic levels. As mentioned, uncertainties in trophic levels play a big role in marine footprint calculations as they impact the yields heavily. To illustrate this, we can use herring. In the 2008 edition herring is put on trophic level 3.68, which leads to a yield

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[7] The figures for the 2014 edition were taken from the *Living Planet Report*, 2014, which does not publish any figures for Norway.

of 0.63 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$]. In the 2014 edition the trophic level was updated to 3.23, leading to a yield of 0.18 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$]. This is a considerable difference and when added up with the changes for other species had a major impact on the results.

5.1.3. "Corrections" of aggregate errors

An aggregation error in the use of yield figures for certain species (in the case of Iceland, cod and halibut) causes major errors in the 2008 edition results. According to the calculations 370.94 t of primary producers are needed to support one tonne of Atlantic cod (*Gadus morhua*). This is because of the species high trophic level (4.42) and means that each hectare of continental shelf yields only 0.01 t of Atlantic cod per year. The problem arises when further down the calculations, in the trade section, all cod species are bundled together and given the yield for Greenland cod (*Gadus ogac*), which is the highest of all the cod species 0.08 (t wha^{-1} y^{-1}). The same thing happens with Greenland halibut (*Reinhardtius hippoglossoides*) yield, although the error is smaller, from 0.01 (t wha^{-1} y^{-1}) to 0.02 (t wha^{-1} y^{-1}). Correcting these errors results in the fishing grounds' footprint dropping from 54.61 gha to 40.78.

In the 2014 edition these yield figures were changed from the highest to the lowest, or 0.01 (t wha^{-1} y^{-1}) for both species. This fixed the problem for Iceland, since these are the correct yield figures for the Icelandic species, but it did not solve the aggregation error. Having the lowest yield will impact heavy exporters, such as Iceland, positively, i.e. will lower their footprint, while nations whose imports outweigh the exports will be negatively affected (assuming the yield is the same for imports and exports).

5.1.4. What is Iceland's marine EF?

The three issues mentioned explain the massive drop in marine footprint between the two editions. This highlights the sensitivity of the calculations. Even the aggregate errors – which on the surface could look like a minor problem – are responsible for 13.83 gha, which in itself is higher than the total footprint of any other country in 2005. This underlines the importance of data accuracy when working with great uncertainty, such as is inherent in the marine calculations. We have demonstrated the importance of accuracy in trophic levels, extraction rates and yield figures but we have not mentioned transfer efficiency nor discard rates. Both of these are also based on estimates in the absence of accurate information.

The bycatch rate given by Pauly and Christensen's equation is a constant 1.27 across all species, meaning that for every tonne of fish caught 0.27 t is discarded.[8] Although there is a clear need for further study into these issues in Iceland, one study by Pálsson et al. (2003) mentions that discard for saithe and redfish is hardly noticeable. A report from the Marine Research Institute (*Mælingar á Brottkasti Botnfiska 2002*[9]) claims that in 2002 the discard rate for cod was around 1% of landings and for haddock 4.9%. To demonstrate how important these figures are we can replace the standard bycatch rate of 1.27 with some kind of average figure for the Icelandic fisheries based on these and use 1.03 as our rate. When this is applied to the Icelandic case the marine footprint of the 2008 edition drops from 54.61 gha to 44.32[10] and from 12,57 to 10,80 gha in the 2014 edition.

Parker and Tyedmers (2012) conclude their estimation of the uncertainties within the marine footprint calculations with the claim that a better understanding of marine ecosystem dynamics (along with improved technology) may increase accuracy of future studies. Rising to the challenge, Luong et al. (2015) propose a new improved method for assessing PPR, by using case specific data to construct a more detailed food web flow matrix which better captures the complexity of the ecosystem in question than the traditional food chain theory. They argue that this will have major implications for assigning trophic levels and transfer efficiency. This would also most likely solve another problem not mentioned here so far, but that is the case species absence from the model, i.e., when species are not included in the models leaving researchers with the choice of putting the species in some "other" category or attempting to find the species most similar, especially in relation to trophic level. For Iceland this was the case with the trade of capelin, blue whiting and other species.

In light of all these estimates and inaccuracies, what is the Icelandic marine footprint? How accurate can we assume the results of the 2014 edition are? Does Iceland really have a marine footprint of 12.57 gha or is there still some way to go with the calculations? According to the Icelandic Directorate of Health, Icelanders consume, on average, 44 kg. of fish per year (Directorate of Health, 2004).When multiplied by the total number of inhabitants 332,529[11] (hagstofa.is, 2017) we get a figure of just under 15 t. This figure is so small that it hardly registers if we try to measure the footprint (assuming this is all haddock, the most commonly eaten fish in Iceland, the footprint per capita is then 0.00018 gha). Added to this would be meal for feed and oils. According to sales figures for a few select years (figures for 2005 were not available) from the Federation of Icelandic Fish Processing Plants (Andersen, 2016) domestic sales of fishmeal and oils range from 4000 to 8000 t and 600–3000 t, respectively. The footprint of this would range somewhere between 0.5 and 2 gha. From this we deduce that with further development of the marine component methodology and calculation model the Icelandic fisheries footprint will end up being close to this (0.5–2 gha) when the export category more or less cancels out the consumption footprint.

Biocapacity calculations for Iceland are likely to be underestimated since the biocapacity of the marine component is only based on the continental shelf even though much of Icelandic fishing takes place outside of it. Important species for Icelandic fisheries, such as capelin, are mainly caught in the open seas and within the fishing limits of other countries. How big this share is of the total catch is difficult to estimate since the concept "continental shelf" is not used in the management of Icelandic fisheries. Areas are not defined by it and it is not at all straightforward to figure out what is caught there and what isn't. To get some indication of the proportion of fishing taking place outside of the continental shelf area we gathered data from the Directorate of Fisheries (Fiskistofa) on fishing in the open seas. The species being caught here were capelin (44,404 t), herring (156,000 t), blue whiting (265,515 t) and redfish (16,019 t). The EF of these amounts to 12.84 gha, which may give some indication of the biocapacity not included in the continental shelf limitation of the methodology. This does not include fishing within foreign fishing limits.

5.2. Issues with Carbon Footprint Calculations

According to the 2008 edition results Iceland has no carbon footprint. This is because the footprint for exports exceeds the sum of the footprints of production and imports. Real data were used for figures of CO_2 emissions of production but a global average intensity was used for the import/export section. This is understandable when it comes to imports, since they come from all over the world and are produced with various different types of energy. The energy used to create the exports

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[8] Although there is no final definition for the word bycatch and it is therefore not clear if this catch is completely discarded, sold in its entirety or a mixture of both (see Alverson et al., 1994), it is assumed here that this is discarded biomass.

[9] Losely translated: *Measuring Discard of Demersal Fish 2002.*

[10] Further uncertainties in the bycatch calculations arise from the fact that bycatch is given the same yield as the primary catch due to a lack of data on the bycatch. This may prove very difficult to resolve, but according to the GFN *Guidebook to the National Footprin:t 2014 edition* an attempt will be made to avoid these assumptions in the next edition of NFA (Lazarus et al., 2014). The same claim was made by Kitzes et al. in the 2008 edition.

[11] Here we could also use the aproximation of 300,000 as the standard methodology does, but since the point is to show how small the consumption is we err on the larger side.

on the other hand is known – at least to some extent. Nearly all of Icelandic energy production is hydro- and geothermally derived electricity. Obviously CO_2 intensities from these are much lower than the global average. When we change the export calculation to reflect this the carbon footprint for exports goes from 13.19 gha to 0.16, which is a difference of 13.03 gha. The carbon footprint of Iceland then changes from 0 to 11.33 gha.

In the 2014 edition this was corrected and local CO_2 intensities were used for exports. This resulted in Iceland having a carbon footprint of 10.74 gha per capita. This is a major step on the way towards a more accurate EF for Iceland due to its heavy use of hydro- and geothermal energy resources.

A roughly estimated breakdown of the Icelandic carbon footprint of imports shows that about 30% of the footprint is due to imports of construction material and machinery, 22% electrical machinery and apparatus, 8% fish and animal products and 6% oil. A multi-region input-output (MRIO) study of the Icelandic carbon footprint would further illuminate this breakdown.

5.3. Minor Issues with Other Land Types

Other minor issues and questions the Icelandic case highlighted involved:

Calculating the Icelandic infrastructure footprint raises two questions: Should land disappearing under infrastructure be considered cropland or would grazing land better capture the productivity of the land being built on? And should we use actual figures for the sizes of reservoirs, since good data for this exists in the country, rather than estimating their size based on the energy production of Icelandic hydroelectric power stations? These changes would likely make the accounts more accurate but the counterargument would be about keeping the method homogenized for better comparisons with other countries. However, implementing both these changes would have only a minor impact on the EF of Iceland. Using 2008 results to demonstrate, then implementing the former change, would change the yield factor for infrastructure from 1.25 to 0.49, which in turn would change the infrastructure footprint from 0.44 gha to 0.17 gha. Using actual data for reservoirs would change the footprint from 0.44 to 0.5 gha. Implementing both changes would result in an infrastructure footprint of 0.25 gha.

For the EF of forests we used the international databank ForesSTAT in line with the methods of GFN since the data found there were quite different from the local data from Statistics Iceland. Categorization was not the same, so in order to aid comparison with other studies we went with the international databank. This caused some 33,000 t of paper, cardboard and paper waste to go unreported, e.g. this was reported at the Statistics Iceland database but could not be fitted into any of the categories of the international one. Since this figure roughly splits in half between the import and export categories this does not significantly affect the outcome but simply adds to uncertainties.

Since the grazing land footprint is limited to the available biocapacity, some demand on the land type (production) goes unaccounted for. For the 2008 edition the estimated demand (unlimited by biocapacity) was 0.66 gha and the for the 2014 edition 1 gha. The unaccounted-for demand (0.41 gha and 0.89 gha, respectively) might be due to a lack of yield figures for derived products or the fact that vast areas of the highland commons are not included in the Corine definition of grazing land and therefore are not counted as such. This latter issue, of course, is not methodological in nature but due to a rather strange management system for the resource (or lack thereof). Furthermore, the method does not include mink farming, so the 37,000 mink in the country also go unaccounted for, meaning that the size of the total livestock is underestimated.

When it comes to cropland, similar problems occur with extraction rates for traded goods, as we saw with the grazing land products. Since imports play a much larger role here than exports we can assume the consumption footprint for the land type should be higher. An interesting finding of the cropland category is that the yield for the land type has been higher than the global average. Barley production plays the biggest role in this. It is surprising that Iceland should yield more barley per square meter than the global average, given its harsh climate. This can possibly be explained with more fertilizer use in Iceland and the fact that the best land is used for the production, and for the long hours of summer daylight. High yields for mushrooms,[12] tomatoes and cucumbers are particularly surprising, but are most likely due to use of greenhouses as well as the summer lack of any darkness.

5.4. Future Research Directions

The aim of this study was to measure the EF of Iceland using local data and to assess how well the method could deal with the exaggerated features of the Icelandic economy, such as the large fisheries in relation to the small population and the near 100% green energy production. We hypothesized that Iceland should make a good case study to test the robustness of the indicator and could highlight its strengths and weaknesses. Our conclusions are that the Icelandic case highlights the strengths of the EF method being the major developments that have happened in the reasonably short time of six years between the two editions of the calculation model we used. The major weakness detected is the great uncertainty and inaccuracies in marine footprint calculations. This study highlights, more than anything else, the importance of further study and development of the marine footprint calculations. Trophic level and transfer efficiency estimates need strengthening - for this a more detailed mapping of the complexities of the marine ecosystem in question, such as proposed by Luong et al. (2015) may be useful – and much work is needed before discard rates can be considered reliable. Yields and extraction rates also need a close examination to ensure accuracy. Aggregation errors for traded goods should be cleared up as soon as possible.

An interesting direction to take with methodological examinations, using Iceland as a case study, would be to utilize the input-output (IO) analysis method as suggested by Wiedmann and Barrett (2010) as an important direction of improvement [methodologically presented by Wiedmann et al., 2006]. The IO approach would likely lead to (1) more comprehensive footprints and (2) more accurate inclusion of the foreign trade. In theory, a proper multi-region IO model would allow using region-specific energy production factors. As presented by Wiedmann et al. (2006), such an approach would also enable analyses of the within-country distribution of the overall footprint bringing EF closer to policy-makers.

6. Conclusion

6.1. Standard EF Method Problems for Small, Highly Specialized Economies

When the standard EF method is applied to the case of Iceland the results indicate that Iceland has the biggest EF in the world. Methodological development and increased accuracy of the calculation model of recent years has brought the Icelandic EF to what seems like a much more realistic figure. Figures of fish consumption from the Icelandic Directorate of Health and the Federation of Icelandic Fish Processing Plants point towards further lowering of the Icelandic EF being in store with continued development of the methodology and the calculation models.

We maintain that the enormous footprints that the two editions of the calculation model used for this study yielded (56.59 and 25.26 gha respectively) are due to the models' inaccuracies, in marine and carbon footprint calculation for the 2008 edition and the marine footprint for the 2014 edition. These are then highlighted by the homogeneity of the

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[12] Almost six times higher for mushrooms than the global average.

Icelandic economy and then further underlined by the small population in relation to the size of those sectors within the economy. Any country with similar economic specialization may be in danger of such distortion in the footprint. If the main sector or sectors are very large in relation to the population, as we see with Iceland, this distortion will be further exaggerated. This may mean, on the other hand, that these countries can be used for methodological honing for their sector of specialization since inaccuracies will be highlighted. This study further illustrates the great importance of data accuracy in EF calculations. This is another reason why countries with highly specialized economies may be useful for methodological improvements since data for their given sector is most likely to be more detailed and accurate than in countries where the same sector plays a lesser role. Due to this importance of data accuracy and the uncertainties inherent in the calculations – especially in marine footprint calculations – the question arises whether using international datasets can ever yield more than a very rough estimate since the data found there are too far removed from the source of data collection.[13]

Due to recent changes in the carbon footprint calculations, this part of the EF now seems to give a realistic result. Without changes in Icelandic consumption patterns or changes in global energy intensities – such as with increased use of renewable energy resources – this component of the Icelandic EF is not likely to decrease. This is most likely enough to ensure that Iceland will continue to have one of the largest national footprints in the world.

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[13] This sentiment was echoed by one of the stakeholders contacted during data collection for the study who felt that once he had fed his data to Statistics Iceland, he could never get their published data to match up with his own (Andersen, 2016).

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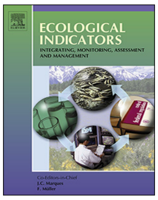

Original Articles

Increasing the accuracy of marine footprint calculations

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ABSTRACT

One of the most used sustainability indicators of the past decades is the Ecological Footprint (EF). Criticism of the EF has often been aimed at its lack of accuracy. The marine component (MF) has been identified as one of the most sensitive parts of the calculations. The aim of this study was to assess and quantify this purported inaccuracy of MF and attempt to highlight its methodological weak points, using Iceland, an economy dominated by the fishing industry, as a case study. Checking for known areas of sensitivity within the calculations, such as trophic levels (TL) and discount rate (DR), MF was calculated based on figures of fish consumption by the Icelandic nation, as estimated by surveys made by the Icelandic Directorate of Health (DoH) and the University of Iceland Nutrition Research Unit (NRU) as well as inland consumption figures from fishmeal and oils from the Association of Icelandic Fish Meal Producers. The results were then compared with results from Global Footprint Network's (GFN) National Footprint Accounts (NFA). The results indicate that the reported sensitivities associated with MF calculations can lead to a seriously distorted outcome. In the case of Iceland this translates to an overestimated MF. For other countries this could show up as underestimated MF, especially for net importers of marine produce. As well as known weak areas such as TL and DR, the study highlights data gaps as the most important source of bias. Filling data gaps with estimates may thus be the most effective way to increase the accuracy of MF.

1. Introduction

Evidence of humanity's overuse of natural resources is mounting, both within the scientific community (Barnosky et al., 2012; Rockström et al., 2009, Millenium Ecosystem Assessment, 2005) as well as in observable changes to the natural world. One reaction to this has been the creation of a wide variety of ways to quantify and highlight these issues. As a result multiple tools and indicators have been created for the purpose. One such indicator is the Ecological Footprint (EF).

In spite of considerable controversy and some hard-hitting criticism (Giampietro and Saltelli, 2014; van den Bergh and Verbruggen, 1999) EF has, since its conception in the early nineties, become the most widely used sustainability indicator in the world (van den Bergh and Grazi, 2015; Talberth et al., 2006). Its metaphoric style and imagery has found favour with practitioners, policy makers and the public alike. This high profile of the indicator brings about a certain responsibility for the scientific community to make EF as accurate and robust as it can be, within its recognized limitations (Wiedmann and Barrett, 2010).

EF's creators William Rees and Mathis Wackernagel and their associates at the Global Footprint Network (GFN), a think tank dedicated to the development of EF, have been actively improving the method for the past twenty-five years (Rees and Wackernagel, 1996; Wackernagel and Rees, 1996; Wackernagel et al., 2002; Monfreda et al., 2004; Wackernagel et al., 2005; Kitzes et al., 2007; Wackernagel et al., 1999; Ewing et al., 2008, 2009, 2010; Borucke et al., 2013) and various suggestions for improvement have appeared in the literature (Pereira and Ortega, 2012; Liu et al., 2014; Niccolucci et al., 2011; Wang et al., 2017; Kissinger and Gottlieb, 2010; Walsh et al., 2009; Liu et al., 2008) as well as derivatives of the method (Jiao et al., 2013). Chambers et al. (2014) have further collated some of this knowledge with the aim of making it more accessible to policymakers and non-technical audiences.

EF methodology uses six land types: cropland, grazing land, forests, fisheries, built-up land (land that disappears under infrastructure) and the hypothetical carbon uptake land, which is the land the methodology assumes is needed to sequester the CO_2 emitted by humans. Each component contains uncertainty, but practitioners working with EF are well aware that the marine component particularly involves large standard errors and a high amount of uncertainty. The material coming from GFN states this explicitly, highlighting estimates of species trophic levels, discount rates and biocapacity as particularly problematic areas

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(Kitzes and Wackernagel, 2009; Lin et al., 2017). However, the literature is surprisingly thin when it comes to methodological improvements of the marine footprint (MF). Of the great number of studies being devoted to methodological improvement suggestions for EF calculations, very few deal specifically with the marine component and its documented inaccuracies.

Ecosystems are complex systems with nonlinearities, thresholds and discontinuities (Costanza et al., 1993) and this applies to marine ecosystems just as much as terrestrial ones. This complexity and variability makes it very hard to set a global sustainable benchmark (Swartz et al., 2010). In addition, marine ecosystems are submerged in water, making them even harder to access. This may, at least partly, explain the lack of studies dealing with MF. Talberth et al. (2006) find one of the biggest downsides to MF is that it seems to indicate that, on a global scale, fisheries are operating within the regenerative capabilities of Earth. This does not correlate with other numerous indications, such as shown by Ludwig et al. (1993), MEA (2005), FAO (2004), Myers and Worm (2003), Pauly et al. (1998), and Pauly and Palomares (2005). Parker and Tyedmers (2012) maintain that the imprecision in MF results is due to uncertainty and natural variability in input parameters. It should also be noted that nearly all the issues mentioned above are not EF specific. Measuring and managing fisheries is a notoriously difficult task - one which humans have often found themselves on the losing side of - as seen in the declining state of the resource as whole and referenced by Talberth et al. (2006). It is this difficulty that Lauck et al. (1998) claim is the most important realization policymakers and scientists must be aware of in order for us to stand a chance of achieving more successful management of the oceans than we have demonstrated since the beginning of the Industrial Revolution. It is therefore vital that much-used metrics such as EF manage to reflect this by accurately capturing the state of the resource - which it is currently not doing - as criticized by Giempietro and Saltelli (2014) and others.

Since transfer efficiency (TE), trophic levels (TL) and discount rate (DR) are all based on estimates, the uncertainty contained in the calculations is considerable. As stated in the *Working Guidebook to the National Footprint Accounts* 2016 (Lin et al., 2017, p. 31):

> *Calculations of the yield for fish are extremely sensitive to the estimated trophic level of the species. These estimates are drawn from average values from* Froese and Pauly (2016)*, many of which have large standard errors. The uncertainty in the fisheries yields for individual species is thus large compared to other products in* ***NFA 2017****.*

In the *Guidebook* the issues highlighted as problematic for the marine footprint are: sensitivity to trophic level estimates and the large standard errors associated with this, the method's inability to convey ecosystem dynamics and the progression of individual stocks which may result in an overestimation of biocapacity, the same discount rate being used for all species and because the data used for the accounts are for total landings (within the given country) and no track is kept on where the fish are caught (e.g. within or outside the waters of the country) it is meaningless to compare national marine EF to national marine biocapacity - as done with other land types of the EF. Kitzes et al. (2009), add to this that estimates for bycatch (discard) are only based on estimates for a single year (FAO, 1971). In addition, as pointed out by Watson and Pauly (2001), catch figures can contain a systemic bias[1]. Estimating biocapacity, or the amount of sustainably harvestable primary production (PP), is in itself fraught with limitations in data and errors of estimation (Pauly, 1996).

This study was aimed at identifying ways to increase the accuracy of MF calculations. To do this Iceland was used as a case study. A recent study shows that when Iceland's MF is calculated using the standard EF method it is substantially larger than any other country's total EF. The enormity of the Icelandic figures can be explained by errors and inaccuracies within the method and data that are magnified by the economic specification of the country and the scale of the fishing industry in relation to the population size (Jóhannesson et al., 2018). The same underlying errors and inaccuracies will affect other countries in the same manner – although they may be less visible (and may work in opposite directions). Countries like China, Norway, Vietnam and the USA are big fish exporters, like Iceland, but these countries do not show up as outliers in the same way Iceland does[2], although they should be affected by the same errors and inaccuracies as Iceland. This makes Iceland a very interesting case in a global perspective and a useful tool to highlight issues with the MF.

In this study the Icelandic MF was calculated with data from survey-based estimates of local consumption figures and the results then compared to results from the National Footprint Accounts (NFA) 2017, which uses the standard MF methodology. The difference in results proves to be considerable: 0.67 global hectares (gha) for the survey-based calculations and 22.26 gha from the standard methodology. Research into the reasons for this difference was then undertaken, highlighting the influence of data accuracy on MF accounting. Particularly it was found that gaps in data, mainly for secondary products, had an impact. Estimates and inaccuracies in data from global databanks also proved problematic. In light of how widely used EF is and how easily errors can go unnoticed within the calculations, increasing the accuracy of the indicator has significant value. This study further shows how the accuracy of MF can be increased with relatively simple measures such as identifying more accurate input data (local data) and filling data gaps with sensible estimates.

2. Methods and research design

The EF calculation method has been constantly evolving since its inception in the mid-nineties (Wackernagel and Rees, 1996; Rees and Wackernagel, 1996) to the latest version published by GFN in Borucke et al. (2013). A recent overview of this development can be found in Lin et al. (2018). The aim of EF is to measure nature's regenerative ability and weigh that up against human resource requirements – or use. To do this it attempts to measure annual primary production in the area under investigation – referred to as biocapacity (BC) – and measure that against the total primary production required for the consumption of its human inhabitants. According to the method's creators Rees and Wackernagel (1996, p. 227) it attempts to answer the question:

> *How large an area of productive land is needed to sustain a defined population indefinitely, wherever on earth that land is located?*

This is based on the idea that all human consumption can be traced to the relevant land type (including sea and water) providing the natural resources needed to produce the goods and services being consumed (Wackernagel et al., 2002). For this purpose the methodology defines six land types: cropland, grazing land, forests, sea and water, built-up land and carbon uptake land.

EF, and its biocapacity counterpoint, is represented by a normalized unit called global hectares (gha). In order to convert the size of the areas into this unit, two co-efficients are utilized to account for the difference in productivity between the land types – equivalence factor (EQF) – as well as the difference in productivity between the same land types in different countries – yield factor (YF).

The general calculation for EF then utilizes these two coefficients to normalize the ratio of production/consumption (P) and the national yield (Y_N) for the product in question as:

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[1] Fishers across the globe systematically underestimate their catch due to economic reasons – except in China where they overestimate it, likely for political reasons.

[2] China: MF 0.08, EF 3.71. Norway: MF 1, EF 6.03. Vietnam: MF 0.05, EF 1.73. USA: MF 0.14, EF 8.37. All figures are for data year 2014.

$$EF = \frac{P}{Y_N} * YF * EQF$$

Once the production footprint is known for all land types, import/export footprints are calculated using the same methods and added to each. These consumption footprints are then added up to form the final EF. EF is then compared to the BC, which is found by area used for production of a given product multiplied by the YF and EQF.

$$BC = \sum_{1} A_{N,i} * YF_{N,i} * EQF_{N,i}$$

Here A is the area available for the production of product i and $YF_{N,i}$ and $EQF_{N,i}$ are the yield and equivalance factors for the land type producing product i.

For a deeper understanding of the standard calculation method for EF readers can refer to the many papers specifically devoted to the purpose, such as Monfreda et al. (2004), Wackernagel et al. (2005), Kitzes et al. (2006), Ewing et al. (2008), Ewing et al. (2010), Ewing et al. (2011), Borucke et al. (2013) and Lin et al. (2018).

2.1. Marine footprint

Like calculations for the other land types, calculations for the MF are based on estimating the average yield of a given area and measuring that against human utilization of that area. Yield estimates are taken from *seaaroundus.org* and are given for primary production. Fish catches are then converted into the primary production required (PPR) to sustain the weight of the catch. For this, species trophic levels (TL) and the rate of transfer efficiency (TE) are utilized. The TE is set at a constant 10% (Pauly and Christensen, 1995) and TL estimates are taken from *fishbase.org*. Another constant added to the equation is a discount rate (DR) for all bycatch, discarded or unreported fish. Taken from Pauly and Christensen (1995), this is set at 27% of all catch. For lack of higher resolution data, the bycatch is given the same TL as the target species.

The equation is thus:

$$PPR = CC * DR * \left(\frac{1}{TE}\right)^{(TL-1)}$$

where CC stands for the carbon content of the wet weight of the fish.

To account for yields lost in trade due to production of goods, extraction rates (Extr.) are used. Yields for derived (D) products are thus found by multiplying the parent (P) product yield with the extraction rate, using world average values.

$$Y_D = Y_P * Extr.$$

2.2. Case study: Iceland

Iceland is a particularly good case to use for studies of fisheries since the marine sector has been the most important sector of the Icelandic economy for the past hundred years. This importance is reflected in catch size in relation to the size of the population and the nation's share of the global catch. This in turn means that any inaccuracies in the calculations are highlighted and made visible, as shown by Jóhannesson et al. (2018).

This study's starting point was the MF for Iceland as calculated and provided by the GFN for the year 2017, according to the latest version of the standard EF method. The Icelandic MF was then calculated again, but this time using actual consumption figures as published in a survey by the Icelandic Directorate of Health and the Unit for Nutrition Research at the University of Iceland (Steingrímsdóttir et al., 2014) as well as figures for inland consumption of fishmeal and fish oils from the Association of Icelandic Fish Meal Producers.[3] Since the two calculations yielded very different results, a thorough examination of the data was conducted in an attempt to identify and explain the difference[4]. Special attention was given to TL, DR and extraction rates (EXTR).

3. Results

The two calculations, the GFN's NFA 2017 calculation - based on data from international databanks as the standard EF method dictates - and the calculation based on data from Steingrímsdóttir et al. (2014), yielded widely disparate results. According to the NFA calculation total Icelandic fish consumption (production and imports with exports subtracted) amounted to 675,630 tonnes. Calculations based on the same standardized GFN method but using data from the UNR/DoH study yielded a result of 27,269 tonnes. The MF according to the NFA was 7,244,682 gha, which amounts to 22.26 gha per capita[5], whereas the MF according to the survey data calculations was 221,836 gha or 0.67 per capita. The results are summarized in Table 1. Below, the potential error sources and the effects of different data and calculation improvements are presented. Biocapacity and population size issues are covered in the last two sub-sections.

3.1. Extraction rates - data gaps

An important finding of the study is the impact data gaps can have on the results. In this case it was gaps in yield data for traded goods due to missing extraction rates. Out of 105 exported seafood commodities in the 2017 NFA, 21 had no yield. This means these exported goods were not accounted for and therefore not subtracted from the Icelandic consumption footprint. A list of the commodities missing yields due to missing extraction rates can be found in the Supporting information (SI) Table S1, along with a description of where the estimates used to fill these gaps were derived from.

When the data gaps in the NFA were filled with estimates based on national EXTR for closely related products or national averages[6] – depending on data availability – the MF dropped from 22.26 gha to 4.57 gha. This way of using estimates follows a similar rationale as used in the method to calculate TL for traded goods from world and national averages, where species level resolution is not available, and should thus be within the boundaries of the method.

3.2. Trophic levels

The NFA uses TL data from fishbase.org, but Fishbase uses averages for each species irrespective of where they live, assuming that the species will seek out organisms on similar steps in the food chain wherever they are in the world (Froese, 2017). Fishbase uses data collected by various means and methods from all over the earth since no standardized, globally agreed upon method exists to estimate TL. This is liable to cause some level of inaccuracy in the Fishbase data or at least inconsistency between areas.

The 2017 NFA accounts use Fishbase data from 2016. Updating this to the 2017 data had a considerable impact on the results, depicting the importance of the accuracy of TL estimates. The change led to a drop in MF from 22.26 gha to 16.82 gha, mainly due to a change in the TL for

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[3] Further details on the survey data calculations can be found in the supporting information.

[4] Since 1990 five such studies have been conducted in Iceland, three for adults and two for children. Results from these were fairly consistent, indicating a declining consumption in fish from 73 g per day in 1990 (Steingrímsdóttir et al.) to 40 and 46 g in 2002 (Steingrímsdóttir et al.) and 2011 (Þorgeirsdóttir et al.) for adults. For children the consumption was estimated at 35 g in 1993 (Steingrímsdóttir et al.) and 27 g in 2006 (Þórsdóttir and Gunnarsdóttir). When the data from the studies showing the highest consumption, the 1990 and 1993 studies, are used, the MF goes from 0.67 gha to 0.93.

[5] The most common way to express EF is per capita.

[6] Calculated from available national extraction rates.

Table 1
NFA 2017 MF results for Iceland and effects of various changes to input data.

Version	Production	Imports[1]	Exports	Total MF
NFA 2017	46.67	1.91	26.31	22.27
Local area size figures	46.63	1.91	26.29	22.25
TL Fishbase 2017	34.71	1.91	19.80	16.82
Local DR (1.1%)	37.14	1.91	20.94	18.11
TL Fishbase 2017 + local DR	27.65	1.91	15.78	13.78
Extr. data gaps estimates	46.67	1.91	44.01	4.57
Extr. est. + TL Fishbase 2017	34.67	1.91	30.14	6.44
Extr. est. + Local DR	37.17	1.91	35.85	3.23
TL F.2017 + Local DR + Extr. est.	27.62	1.91	23.60	5.93
Local TL (P&V,2000)	20.59	1.91	12.12	10.38
Local TL + Extr. est.	20.62	1.91	24.21	−1.82
Local TL + Extr. est. + DR	16.42	1.91	20.07	−1.74
EF based on UNR/DoH survey	0.67	0.01	0.01	0.67

[1] Since most changes involve local data, we have kept the imports unchanged.

cod from 4.1 to 4.42.

Local data for TL are not readily available. Only one study (Valtýsson and Pauly, 2003) could be found providing the TL specifically for Iceland. Using this data reduced the MF from 22.26 gha to 10.38. A table showing the difference in the TL between these different sources can be found in SI Table S7.

3.3. Discount rate

According to the standard EF method, DR is a constant 27% across all species based on Pauly and Christensen (1995). In Iceland the Marine Research Institute has gathered data on discards since the year 2000. Data for cod and haddock have been gathered consistently each year and are considered robust by the project's leader (Pálsson, 2017).

According to these data average discards for haddock in the years 2001 to 2015 was 1.38% of landings (weight), with the highest figure being 4.75% (2003) and the lowest 0.01% (2014). For cod, for the same period, the average was 0.81%, with the highest figures being 2.41% (2001) and the lowest 0.05% (2011). When the 27% figure used by the GFN was replaced with an average of the two local figures (averages for 2001–2015) of 1.1% the MF dropped from 22.26 gha to 18.11 gha.

It should be clearly stated that using the DR for cod and haddock as a proxy for all other commercial and non-commercial species can hardly be considered an accurate estimate, but these are the only robust figures available for the country.

3.4. Summary of different effects

The changes with the biggest impacts are filling data gaps with estimates, such as using the yield for fresh or chilled salmon to fill the gap in yield for frozen salmon, and using local TL figures. When these two changes are implemented into the NFA the MF drops from 22.27 to −1.82 gha. Since gha is never shown as negative this would show up as 0 in the accounts. This and the results from other changes made to the input data during the study are shown in Table 1 below.

3.5. Biocapacity

The latest published estimates of the NPP in the sea around Iceland, identified by this study, came from Zhai et al. (2012). Using the NPP of 602.74 from this study for the entire Icelandic fishing area (including Arctic water, polar water, Atlantic water, mixed water and the continental shelf[7]) leads to a change in biocapacity for the marine component from 12.24 gha to 14.95, which in turn takes the total biocapacity for Iceland, including marine and terrestrial areas, from 31.56 to 34.27 gha. Excluding everything except the continental shelf – as EF methodology currently dictates – the primary production is estimated at 767.12 mg per day, which takes the marine biocapacity to 18.96 gha and the total biocapacity to 38.28 gha.

Changing the size of the continental shelf area around Iceland from 109.010 km^2 as given by the NFA and wri.org, to a local figure from the Hydrographic Department of the Icelandic Coast Guard of 113.970 km^2 (Vésteinsson, 2017) increases the MF biocapacity from 12.24 gha to 12.79 gha.

A sizable part of the Icelandic catch is actually caught on the high seas and within the fishing limits of other nations, as a part of bilateral agreements. The inclusion of these areas would raise the biocapacity further (Jóhannesson et al., 2018).

3.6. Population size

Local figures for the Icelandic population for the end of 2013 (the data year of the 2017 NFA) can be found at Statistics Iceland. The NFA 2017 figure is 325,391. Statistics Iceland has a figure of 325,671. Using this local figure changes the MF from 22.26 gha to 22.25 gha and thus has a minor impact on the results

In order to further examine the relationship between the size of a population to the size of its fisheries (or other sectors affecting the EF) a hypothetical example of the population of Spain was used to insert into the calculations, since the Spanish fisheries are of a similar size to the Icelandic[8]. Changing the population figure to the size of the Spanish population of 46 million changed the MF from 22.26 to 0.16 gha. This hypothetical change illustrates how it is the size of the Icelandic fisheries in relation to the population size that highlights the inaccuracies within the MF accounts, as pointed out by Jóhannesson et al. (2018).

4. Discussion

This study confirmed certain sensitivities within MF calculations that have already been pointed out in the literature, such as TL and DR (Kitzes and Wackernagel, 2009; Lin et al., 2017) and inclusion/lack of extraction rates for traded commodities (Jóhannesson et al., 2018). Further, this study quantified some of these issues and showed how what seem like minor inaccuracies in data can have detrimental impacts on the results. This can be seen in how a change in TL for a single species, such as in the case for cod between 2016 and 2017 from 4.42 to 4.1 can change the result by 1.16 gha. This is further illustrated when data gaps for 21 seafood commodities are filled with estimates and the results were thus changed by 17.69 gha. Considering that the EF accounts consist of thousands of data entry points it doesn't take many such inaccuracies until the results have lost all touch with reality. This may cast doubt on the current practise of GFN to publish annual NFAs based on international databanks. The question must therefore arise, if EF results are expected to resemble reality at all, whether it does not call for a thorough study of each and every data entry to ensure as much accuracy as possible?

Accuracy of the TL plays a key role in the MF and the Fishbase data used for the NFA likely contain too much uncertainty to accurately portray the TL of all species globally. It seems that this problem is

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[7] It should be noted that the data, as it appears in the study, includes both temporal and spatial variants that are not taken into account here. This adding up of data from different times and areas in order to get an annual daily

(*footnote continued*)
average, as required by EF calculations, is done on the sole responsibility of the authors of this study and might not have the approval of the authors of Zhai et al. (2012).

[8] Total catch with aquaculture was 1326 thousand tonnes in Iceland in 2015 and 1195 thousand tonnes in Spain EUROSTAT (2017). *Fishery statistics in detail* [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Fishery_statistics_in_detail [Accessed].

outside the scope of the EF method since the issue may likely lie with the fact that currently there are no universal ways of estimating TL and the figures in Fishbase reflect this. Therefore the Fishbase TL data are actually averaged estimates from various areas, gathered with various methods. The NFA would undoubtedly benefit from TL data that were gathered by the same methods the world over. Using the local TL figures from Valtýsson and Pauly (2003) lowers the MF considerably, highlighting the importance of data, and locally sourced data seem more accurate than data derived from international databanks.

If assuming that the survey results of 0.67 gha MF for Iceland is the figure most accurately reflecting reality, then using local TL figures seems to improve the accuracy of EF. Filling the Extr. data gaps with estimates seems the most obvious way to increase the accuracy and putting those two changes together yields a result closest to the goal of 0.67. Although adding the local DR moved the result slightly closer to the 0.67 gha mark, the lack of data supporting the DR discounts its accuracy. The limited DR data are unfortunate and the question remains whether the data for cod and haddock are indicative of a certain culture around discards in Iceland or if they are lower than average since these are valued species? According to a recent study by Pauly and Zeller (2016) global discards have been declining since the late 1980s, which could indicate a global trend away from discards. Icelandic fisheries may be developing along with this trend, but further data are needed to verify that. The same study by Pauly and Zeller (2016) further claims that global DR in 2000–2010 was less than 10%. This suggests a strong upwards bias in the 27% global DR used by the standard EF method.

A surprising finding of the study is how big the negative impact of data gaps is on the results. This proved to be the largest source of bias in the study. This further emphasises the importance of data accuracy, as pointed out by Parker and Tyedmers (2012). Filling those gaps with estimates proved relatively straightforward when using existing data used elsewhere for the NFA and had a dramatic impact on the results. Solving this issue for future NFAs should therefore be a relatively simple matter and has the potential to increase the accuracy of the accounts considerably. Manual proofreading of the NFAs to fill in data gaps with estimates is thus likely to drastically improve the accuracy of the accounts.

Biocapacity is another component of the footprint methodology that has been pointed out as sensitive and likely overestimated. This study found that using the latest published data for PPR in the seas around Iceland, from a study using remote sensing as called for by Parker and Tyedmers (2012), as well as available ship data (Zhai et al., 2012), actually seemed to indicate that the PPR on the continental shelf is higher than assumed by the NFA and leads to a 55% increase in marine biocapacity.

As pointed out by Jóhannesson et al. (2018) the size of the population in relation to economic activity is of importance, as is highlighted when the population of Iceland is changed to the population of Spain, a country with fish production similar to that of Iceland, and the problematic MF, with all its data gaps and inaccuracies, drops from 22.26 gha to 0.16. In this manner errors and inaccuracies within the accounts for countries with larger populations can be diffused by scale and therefore go undetected, and the results potentially lead to biased policy suggestions.

5. Conclusions

This study aimed at identifying bias and increasing accuracy of the marine (fisheries) component of Ecological Footprint calculations, as conducted by the Global Footprint Network (the standard method of EF calculations).

The study highlights the importance of data accuracy and identified data gaps as the largest source of bias. The study further illustrates how relatively few and minor inaccuracies can have detrimental effects on the results. The use of local data and actual hard data as opposed to general estimates are also shown as important, especially for known areas of sensitivity such as trophic levels, discount rates and biocapacity.

This study indicates that the input data used for the Global Footprint Network's National Footprint Accounts may be too inaccurate and contain too many gaps to be able to yield realistic results. This begs the question if publishing annual accounts based on international databases may be more harmful than helpful to the method, its development and image. This may be bad news for the National Footprint Accounts annual publication but good news for the method, since it may help answer some of the criticism aimed at the Ecological Footprint, such as why the fisheries component seems to indicate globally sustainable fishing practises.

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Appendix A. Supplementary data

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Supporting information

Increasing the accuracy of marine footprint calculations

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Missing extraction rates

Table S1 below, shows the commodities that were missing extraction rates (and therefore yields) as well as the commodities used as proxies and their yields.

Table S1 Missing extraction rates, estimate basis and yields

Products missing extraction rates	Estimates taken from	[t ww fish (ha shelf)$^{-1}$ yr^{-1}]
Atlantic and Danube salmon, frozen	Atlantic and Danube salmon, fresh or chilled	0.06
Caviar	National average yield for all fish species (excluding shellfish)	0.1
Caviar substitutes	National average yield for all fish species (excluding shellfish)	0.1
Coalfish (=Saithe), frozen	Coalfish (=saith), fresh or chilled	0.01
Cod (Gadus spp.), frozen	Cod (Gadus morhua, Gadus ogac, Gadus macrocephalus), fresh or chilled	0.01
Fish fillets, frozen, nei	Fish fillets, frozen, nei	0.05
Fish heads, tails and maws, dried, salted or in brine, smoked	National average yield for all fish species (excluding shellfish)	0.1
Fish livers and roes, dried, salted or in brine, smoked	National average yield for all fish species (excluding shellfish)	0.1
Fish livers and roes, frozen	National average yield for all fish species (excluding shellfish)	0.1
Fish waste	National average yield for all fish species (excluding shellfish)	0.1
Flat fish, fillets, fresh or chilled	National average yield for flat fish	0.07
Flat fish, fillets, frozen	National average yield for flat fish	0.07
Livers and roes, fresh or chilled	National average yield for all fish species (excluding shellfish)	0.1
Other edible fish offal, dried, salted or in brine	National average yield for all fish species (excluding shellfish)	0.1
Other freshwater and saltwater fish, frozen	Other freshwater and saltwater fish, frozen	0.05
Other Pacific salmon, frozen	Other Pacific salmon, frozen	0.08
Sea cucumbers, other than live, fresh or chilled	National yield for molluscs	2.39
Sea cucumbers, prepared or preserved	National yield for molluscs	2.39
Seaweeds and other algae, fit for human consumption	National yield for seaweeds	3014
Seaweeds and other algae, unfit for human consumption	National yield for seaweeds	3014
Trout, frozen	Trout, frozen	0.1

Estimates for yields for the category *Atlantic and Danube salmon, frozen* were taken from yields for the category *Atlantic and Danube salmon, fresh or chilled*, 0.06 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$]. *Caviar and caviar substitutes* have no obvious corresponding category so the national average yield for all fish species (excluding shell fish) is used, 0.1 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$]. The same goes for *Fish livers and roes*, *Other edible fish offal* and *Fish waste* as well as *Fish heads, tails and maws*. These categories could arguably have a lower or higher yield but the lower the yield the higher the export footprint, which leads to a lower footprint of consumption.

Coalfish (=saith), frozen is based on *Coalfish (=saith), fresh or chilled*, 0.01 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$], *Cod (Gadus spp.), frozen* is based on *Cod (Gadus morhua, Gadus ogac, Gadus macrocephalus), fresh or chilled,* 0.01 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$], *Fish fillets, frozen, nei* are based on a category with the same name but a different HS Code (The Harmonized Commodity Description and Coding System – an international naming system for traded commodities)[1], 0.05 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$] and so are *Other freshwater and saltwater fish, frozen,* 0.05 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$], *Trout, frozen*, 0.1 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$] and *Other Pacific salmon, frozen*, 0.08 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$].

Flat fish, fillets, fresh or chilled and *Flat fish, fillets, frozen* are based on a national average yield for flat fish, 0.07 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$], *Sea cucumbers, other than live, fresh or chilled* and *Sea cucumbers, prepared or preserved* get the national yield for molluscs, 2.39 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$]. *Seaweeds and other algae, fit for human consumption* and *Seaweeds and other algae, unfit for human consumption* get the national yield for seaweeds 3014 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$].

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[1] Another option here would have been to base it on *Fish fillets, fresh or chilled, nei.* This would have increased the yield to 0.07 [t ww fish (ha shelf)$^{-1}$ yr $^{-1}$], leading to a lower export footprint and a higher MF or 4.6 gha.

Survey data

National surveys of the dietary habits of Icelanders were first conducted in 1939 (Kristjánsdóttir and Hilmarsdóttir, 2010). The last three were published in the years 2011 (Þorgeirsdóttir et al), 2002 (Steingrímsdóttir et al) and 1990 (Steingrímsdóttir et al), yielding results of 46, 40 and 73 grams of fish consumed per day per person (18-80 years old) respectively, indicating a decline in fish consumption in the past thirty years. Studies for children aged around 9 – 15 were published in 2006 (Þórsdóttir and Gunnarsdóttir) and 1993 (Steingrímsdóttir et al) respectively yielding results of 27 and 35 grams per person per day on average.

Here, results from the most recent study are used, 46 grams per day on average is used for adults between the ages of 18 and 80. For children under 18 results from the 2006 and 1993 studies were compared with results for adults in the same decade and the ratio between adult and child portions in each decade found. An average of these two figures was then used to find the ratio for this decade, in which no study on children has been done yet. The average consumption for children under 18 is thus estimated at 27 grams per day per person, as shown in table S2 below. Shaded areas show the estimates based on the previous studies.

Table S2 Portion size ratios between adult and children fish intake

Decade	Children g p/d	Adults g p/d	Ratio Ch/A
2010	27	46	0,58
2000	27	40	0,68
1990	35	73	0,48

The 27 g figure used for children under 18 years of age was also used for citizens over 80 years old. Infants under one year old were excluded.

Table S3, below, shows the number of people between the ages of 18 and 80, children under the age of 17 and adults over 80 years old as well as infants, although they were not included in the study. Presented are these demographic groups of the Icelandic population at 1. January 2014. Data come from Statistics Iceland (2017).

Table S3 Icelandic population, 1. January 2014

Demographic group	Count
Adults	235170
Children and elderly	86176
Infants (not included)	4556
Total	325902

The number of people is then multiplied with the relevant g p/d figure from table S2, as shown in table S4 below.

Table S4 Estimated total fish consumption 2013

Demographic group	g p/yr
Estimated consumption, adults	3948504300
Estimated consumption, children and elderly	849264480
Total	4797768780

Total consumption in 2013 is thus 4797,8 tonnes.

Table S5, below, shows a further breakdown of the number of people of any given age in the year 2013.

Table S5 Icelandic population 2013

Age	Pop	Age	Pop	Age	Pop	Age	Pop	Age	Pop	Age	Pop	Age	Pop
1 árs	4556	18 ára	4477	35 ára	4293	52 ára	4122	69 ára	2436	81 ára	1321	98 ára	34
2 ára	4509	19 ára	4737	36 ára	4123	53 ára	4358	70 ára	2312	82 ára	1271	99 ára	14
3 ára	4879	20 ára	4981	37 ára	4332	54 ára	4381	71 ára	2172	83 ára	1250	100 ára	16
4 ára	4884	21 ára	4937	38 ára	4314	55 ára	4169	72 ára	1882	84 ára	1064	101 ára	4
5 ára	4726	22 ára	4878	39 ára	4158	56 ára	4153	73 ára	1734	85 ára	958	102 ára	7
6 ára	4557	23 ára	5137	40 ára	4476	57 ára	4073	74 ára	1681	86 ára	842	103 ára	2
7 ára	4451	24 ára	4821	41 ára	4530	58 ára	3912	75 ára	1592	87 ára	759	104 ára	3
8 ára	4384	25 ára	4958	42 ára	4110	59 ára	3755	76 ára	1572	88 ára	639	105 ára	0
9 ára	4362	26 ára	4487	43 ára	3880	60 ára	3711	77 ára	1526	89 ára	524	106 ára	1
10 ára	4220	27 ára	4333	44 ára	4042	61 ára	3485	78 ára	1469	90 ára	462	107 ára	2
11 ára	4088	28 ára	4420	45 ára	4034	62 ára	3377	79 ára	1415	91 ára	376	108 ára	0
12 ára	4202	29 ára	4553	46 ára	4117	63 ára	3373	80 ára	1356	92 ára	299		
13 ára	4416	30 ára	4636	47 ára	4393	64 ára	3195			93 ára	214		
14 ára	4250	31 ára	4727	48 ára	4364	65 ára	3112			94 ára	147		
15 ára	4324	32 ára	4646	49 ára	4421	66 ára	2920			95 ára	120		
16 ára	4402	33 ára	4820	50 ára	4388	67 ára	2712			96 ára	73		
17 ára	4505	34 ára	4653	51 ára	4349	68 ára	2690			97 ára	59		
	75715		80201		72324		61498		21147		10378		83

In order not to underestimate the MF it is assumed that Icelanders only eat fillets, therefore for the rest of the fish needs to be accounted for as well, assuming it is wasted, i.e. not used for fishmeal etc. The Steingrímsdóttir et al, 2012 survey gives a rough breakdown of the amounts of the different types of fish products as:

	Cod/haddock	Salmon/trout	Other	Dried fish
g per day	26	6	13	1,3

There is no indication of the breakdown between the species that are listed together here so it is assumed there is a 50/50 split between them, so cod 13 g per day per person, haddock 13 g per day… etc. Then each product's percentage of the whole is calculated as show in table S6, below. Because the survey data only covers human consumption of fish we have to add consumption of fishmeals and –oils, both local production and imports. These numbers are included in figures from the Association of Icelandic Fish Meal Producers.

The FishStat figures used by the standard EF methodology give an extraction rate for frozen cod fillets of 0,58, for haddock 0,52, for salmon 0,45 and for trout 0,74. For the "other" category the extraction rate for *Other fish fillets, dried, salted or in brine, not smoked* of 0.53 in the GFN model is used. For the "dried" category the extraction rates are taken from *Other fish, dried, whether or not salted but not smoked*, which is 0.31. According to the sheet *fish_group_yield_n* in the GFN model, the average yield for all local fish is 0.07. This is the same yield long rough dab has and the other category is therefore listed as such in the production sheet *efp.*

According to the Association of Icelandic Fish Meal Producers, consumption of fishmeal in Iceland in 2013 was 3636 tonnes and oils 972 tonnes. Extraction-/conversion rates for meal and oil are calculated from actual figures from the Association of Icelandic Fish Meal Producers. The total amount of raw material for rendering was 621.280 tonnes and from that 121.827 tonnes of meal were produced. The extraction rate is thus 0,2. The make up of the meal is 65% capelin (11.807 tonnes), 15% blue whiting (2727 tonnes), 12% herring (2182 tonnes) and 8% mackerel (1454 tonnes). Meal and oil are rendered from the same input, therefore converting both consumption figures to whole fish would be double counting. Table S6, below, shows the estimated consumption of each of the six categories identified by Steingrímsdóttir et al, 2012, as well as consumption of fishmeal and fish oils.

Table S6 Estimated consumption of different fish products

Fish	Total cons.	% of total	Extr. Rate	Estim. Consumption
Cod	4798	0,28	0,58	2316
Haddock	4798	0,28	0,52	2584
Salmon	4798	0,07	0,45	746
Trout	4798	0,07	0,74	454
Other	4798	0,28	0,53	2535
Dried	4798	0,03	0,31	464
Meal/oils	3636	1	0,2	18180
Total				**27279**

When these figures are imported into the GFN model the result is MF of 0.67 gha. All figures are registered on the production side, except dried fish, which is entered as imports since there is no dried fish category under the production account.

Tropic levels

Table S7, below, shows the difference in trophic levels between NFA 2017 (Fishbase 2016), Fishbase 2017 and the Valtýsson and Pauly, 2000 study.

Table S7 TL's, NFA 2017, Fishbase 2017, Valtýsson and Pauly, 2000

Icelandic name	Common name	Latin	P&V, 2000	Fishbase 2017	GFN 2017
Þorskur	Cod	Gadus morhua	4	4,1 ±0.2	4,42
Ýsa	Haddock	Melanogrammus aeglefinus	3,4	4 (±0.1)	4,09
Ufsi	Saithe	Pollachius virens	3,7	4,3 (±0.4)	4,38
Túnfiskur	Atlantic bluefin tuna	Thunnus thynnus		4.5 ±0.8	4,43
Karfi	Redfish	Sebastes marinus (Sebastes Norwegius)	3,3	4 (±0.68)	4,04
Djúpkarfi	Beaked redfish	Sebastes mentella	3,3	4.1 ±0.66	3,65
	Atlantic redfishes nei	Sebastes spp	3,3		3,68
Litli karfi	Norway redfish	Sebastes viviparus	3,3	4.0 ±0.67	4,03
Steinbítur	Atlantic catfish	Anarhichas lupus	3,5	3,6 (±0.0)	3,24
Hlýri	Spotted wolffish	Anarhichas minor	3,5	3,6 (±0.51)	3,45
Langa	Ling	Molva molva	3,8	4,4 (±0.2)	4,25
Blálanga	Blue ling	Molva dypterygia	3,8	4,5 (±0.6)	4,48
Keila	Tusk	Brosme brosme	3,8	3,9 (±0.3)	4
Litli langhali?	Grenadier	Nezumia aequalis	3,8	3.3 ±0.1	
Tindaskata	Starry ray	Amblyraja radiata	3,7	4.2 ±0.3	4,02
Skötuselur	Monk	Lophius piscatorius		4.5 ±0.1	4,45
Skata	Skate	Dipturus batis	3,7	3.5 ±0.6	3,96
Lýsa	Whiting	Merlangius merlangus	3,8	4.4 ±0.2	4,37
Silfurloðna	European smelt	Osmerus eperlanus	3,2	3.5 ±0.42	3
Háfur	Spiny dogfish	Squalus acanthias	3,7	4.4 ±0.4	4,3
Hákarl	Greenland shark	Somniosus microcephalus	4,6	4.2 ±0.6	4,22
Hvítaskata	Sailray	Raja lintea	3,7	3.6 ±0.50	3,62
Náskata	Shagreen ray	Raja fullonica	3,7	3.5 ±0.37	3,5
Lúða	Halibut	Hippoglossus hippoglossus	4	4.0 ±0.5	4,53
Grálúða	Greenland halibut	Reinhardtius hippoglossoides	4	4.4 ±0.1	4,48
Skarkoli	Plaice	Pleuronectes platessa	3,2	3.2 ±0.50	3,26
Þykkvalúra	Lemon sole	Microstomus kitt	3,2	3.6 ±0.1	3,25
Langlúra	Witch	Glyptocephalus cynoglossus	3,2	3.2 ±0.2	3,14
Stórkjafta	Megrim	Lepidorhombus whiffiagonis	3,2	4.3 ±0.1	4,24
Sandkoli	Dab	Limanda limanda	3,2	3.4 ±0.64	3,29
Skrápflúra	Long rough dab	Hippoglossoides platessoides	3,2	4.1 ±0.0	3,65
Síld	Herring	Clupea harengus	3,3	3.4 ±0.1	3,23
Loðna	Capelin	Mallotus villosus	3,3	3.2 ±0.1	3,15
Kolmunni	Blue whiting	Micromesistius poutassou	3,5	4.1 ±0.3	4,01
Makríll	Mackerel	Scomber scombrus		3.6 ±0.2	3,65
Spærlingur	Norway pout	Trisopterus esmarkii	3,5	3.2 ±0.0	3,24
Humar	Norway lobster	Nephrops norvegicus	2,5		2,6
Rækja	Shrimp	Pandalus borealis	2,3		2,46
Hörpudiskur	Scallop	Chlamys islandica	2,1		
Beitusmokkur	European flying squid	Todarodes sagittatus			4,01
Vogmær	Dealfish	Trachipterus arcticus		4.5 ±0.62	4,5
Kræklingur	Blue mussel	Mytilus edulis			2,1
Stinglax	Black scabbardfish	Aphanopus carbo		4.5 ±0.77	4,48
	Wolffishes (catfishes)	Anarhichas spp	3,5		3,48
Kúskel	Ocean quahog	Arctica islandica	2,1		2,1
	Argentines	Argentina spp		3.6 ±0.52	3,43
Þang	North Atlantic rockweed	Ascophyllum nodosum	1		1
Beitukóngur	Whelk	Buccinum undatum	2,5		2,1
Geirnyt	Rabbit fish	Chimaera monstrosa	3,2	3.5 ±0.0	3,5
Slétthali	Roundnose grenadier	Coryphaenoides rupestris	3,8	3.5 ±0.49	3,54
Hrognkelsi	Lumpfish(=Lumpsucker)	Cyclopterus lumpus	3,5	3.9 ±0.0	3,89
Urrari	Grey gurnard	Eutrigla gurnardus		3.9 ±0.0	3,57
Sæbjúgu	Sea cucumbers nei	Holothuroidea			2,3
Búrfiskur	Orange roughy	Hoplostethus atlanticus		4.3 ±0.1	4,3
Hrossaþari	Tangle	Laminaria digitata	1		1
Þari	North European kelp	Laminaria hyperborea	1		1
Snarphali	Roughhead grenadier	Macrourus berglax		3.6 ±0.53	4,48
Lax	Atlantic salmon	Salmo salar		4.5 ±0.3	4,43
Urriði	Sea trout	Salmo trutta		3.4 ±0.1	3,16
Bleikja	Arctic char	Salvelinus alpinus		4.4 ±0.5	4,26

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Data accuracy in Ecological Footprint's carbon footprint

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ABSTRACT

Since the UNCED‘s call for the creation of sustainability indicators many such have been put forth in the literature. One of the more successful ones, in terms of popularity, is the Ecological Footprint (EF). Much criticism has been directed at the EF, not least the carbon uptake component (CF). The CF typically makes up around 50% of global EF and is the sole cause for its overshot – i.e. results indicating unsustainable consumption. The aim of this study was to assess the accuracy of the data used for the calculation of CF. The study finds that the data is lacking in accuracy to the point that stating that CF or EF is any given number at any given time is misleading. The reasons for this uncertainty are identified as use of estimates and averages for the calculations as well as discrepancy between data collected locally and data from international databanks. CF or EF results should thus always be prefaced with caveats regarding the uncertainty involved in the estimation. The lack of caveats in EF dissemination is worrying and has led to the most serious criticism of the method to date, that of it fulfilling the criteria for pseudo-science for failing to disclose uncertainties in calculations and results. This study suggests that the reason for this failure may be traced to the Global Footprint Network (GFN) being both a think tank actively promoting the use of EF, and the world's largest research unit into the methodology. This can lead to uncertainties being down played in dissemination not to confuse current users of the method or dissuade new ones. The study further raises questions about the accuracy of GHG estimates in general since they are often based on the same IPCC default emission factors and activity data as used by the GFN.

1. Introduction

Human endeavour invariably impacts the natural environment in which we live. Examples from history suggest that when this impact exceeds nature's inherent regenerative capacity it can lead to substantial changes to the complex web of life that makes up earth's ecosystems, which is turn can negatively impact people's quality of life and the robustness of the natural systems (Barnosky et al., 2012; Motesharrei et al., 2014; Roman et al., 2018). This has led to a call for ways to measure human impact on the natural world through so called sustainability indicators (UNCED, 1992).

Quantifying this impact on the environment is not a simple task and many indicators have been created in the past decades (Cobb and Cobb, 1994; Wackernagel and Rees, 1996; Lawn and Sanders, 1999; Hanley, 2000). One of these indicators is the Ecological Footprint (EF) (Rees and Wackernagel, 1994; Wackernagel and Rees, 1996).

The EF falls under a category of aggregate sustainability indicators (van den Bergh and Grazi, 2013). This means that large sets of data are aggregated into one final figure which should indicate the level of sustainability or unsustainability as the case may be. EF has been studied and used extensively in a wide variety of settings from a product level (Frey et al., 2006; Limnios et al., 2009; Hanafiah et al., 2012) to national levels (Haberl et al., 2001; Medved, 2006; Galli et al., 2012; Wang et al., 2012; Salvo et al., 2015; Solarin et al., 2019) and the whole Earth (WWF 2018). EF is supported by a think tank, the Global Footprint Network (GFN), dedicated to its development and distribution. GFN publishes annual accounts of global footprints and that of humanity as a whole in the National Footprint Accounts (NFA).

Abbreviations: EF, Ecological Footprint; CF, Carbon footprint (as defined by EF); GFN, Global Footprint Network; NFA, National Footprint Accounts; P, Production (under CF – CO2 emissions); OSFr, Ocean sequestration fraction rate; AFCS, Average forest carbon dioxide sequestration; EQF, Equivalence factor; IPCC, Intergovernmental panel on climate change; NPP, Net primary production; PP, Primary production; GAEZ, Global Agro-ecological Zones; BC, Biocapacity; gha, Global hectares; YF, Yield factor; IEA, International Energy Agency; SI, Supplementary information; GLs2006, IPCC Guidelines for national greenhouse gas inventories; EA, Icelandic Environment Agency; NEA, National Energy Authority (Iceland); GHG, Greenhouse gas; NCV, Net calorific value; CC, Carbon content; COF, Carbon oxidation factor; CDIAL, Carbon dioxide information analysis centre

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Since its conception in the early nineties (Rees and Wackernagel, 1994; Wackernagel and Rees, 1996), EF has become an established sustainability indicator and, according to some researchers, one of the most used in recent years (Venetoulis and Talberth, 2008; van den Bergh and Grazi, 2015). The popularity of the EF (or in the words of Giampietro and Saltelli (2014a, p. 620): "*The extraordinary success enjoyed by the Ecological Footprint…*") has not been realized without criticism to the method (Gordon and Richardson, 1998, van den Bergh and Verbruggen, 1999, VROMraad, 1999, Ayres, 2000, Moffatt, 2000, Opschoor, 2000, van Kooten and Bulte, 2000, EAI, 2002, Grazi et al., 2007, Lenzen et al., 2007, Fiala, 2008, van den Bergh and Grazi, 2010, Blomqvist et al., 2013a; Blomqvist et al., 2013b, van den Bergh and Grazi, 2014a,b; Giempietro & Saltelli, 2014a,b; van den Bergh and Grazi, 2015).

An important criticism that has been raised is the fact that of the six land types used in EF only one, carbon uptake land (land needed to sequester human CO2 emissions), seems to be utilized unsustainably on a global scale (van den Bergh and Verbruggen, 1999; Lenzen et al., 2007; Giampietro and Saltelli, 2014). This does not match other indications being reported in the literature (MEA, 2005; Turner, 2008; Rockström et al., 2009; Niccolucci et al., 2012; Barnosky et al., 2012; Kubiszewski et al., 2013; Steffen et al. 2015; WWF, 2018). Hence, if the carbon uptake land type was removed from the EF it would indicate that humans were living within the regenerative capacity of planet earth – or in other words, living sustainably. This makes the carbon component of EF an important area of study.

EF's carbon footprint (CF) is made up of four components: Production (emissions) data (P), fraction of CO2 sequestered by the ocean (OSFr), a yield factor – made up of global forest average carbon sequestration rate (AFCS) divided by ratio of C and CO2 – and a so called equivalence factor (EQF) intended to normalize the difference in productivity between the six land types that make up EF. These components have been dealt with in previous studies, at least to some extent.

Giampietro and Saltelli (2014a) have pointed out the difficulty with attaining reliable figures for any of these variables making up the CF equation. They particularly highlight the ocean sequestration fraction rate (OSFr) as problematic in this respect and point to McKinley et al. (2011) and Wanninkhof et al. (2012) to support their claim. GFN's calculations of OSFr are based on the findings of Khatiwala et al. (2009) and personal correspondence with the researchers (Guidebook, 2016). In the study in question Khatiwala et al. (2009) claim that the oceans sequester 20–35% of anthropogenic CO2 and state that:

> "…considerable uncertainties remain as to the distribution of anthropogenic CO2 in the ocean, its rate of uptake over the industrial era, and the relative roles of the ocean and terrestrial biosphere in anthropogenic CO2 sequestration." (p. 346)
>
> They go on to explain that…:
>
> *"A key challenge for estimating anthropogenic CO2 (C_{ant}) in the ocean is that C_{ant} is not a directly measurable quantity. Existing estimates of the C_{ant} are thus based on indirect techniques, such as so-called 'back calculation' methods that attempt to separate the small anthropogenic perturbation of carbon by correcting the measured total dissolved inorganic carbon (DIC) concentration for changes due to biological activity and air-sea disequilibrium." (p.346)*

Global Footprint Network (GFN) uses 30% as the ocean sequestration fraction.

Blomqvist et al. (2013a) have pointed out how the overshot of carbon uptake land rests on a single determinant – the average forest carbon sequestration rate (AFCS). They go on to explain how suspect this is in light of natural variability in sequestration rates and uncertainties in their measurement. In 2016, Mancini et al. – a group of GFN associated researchers – published a study focusing on refining the AFCS estimation. Their findings were that AFCS was lower than assumed by the standard EF methodology and therefore global CF was higher. In their review of this key parameter within CF, Mancini et al. (2016), estimate the average forest carbon sequestration rate at 0.73 t C ha^{-1} yr^{-1}, with a standard error of ± 0.37 t C ha^{-1} yr^{-1}. That is a 50% standard error. This study forms the basis of AFCS in current CF calculations of EF.

The equivalence factor (EQF) variable and its basis in the United Nation FAO suitability indexes from the Global Agro-Ecological Zones (GAEZ) model has been criticized by Venetoulis and Talberth (2008) who proposed a new method of estimating EQF based on net primary production (NPP).

Although Giampietro and Saltelli (2014a) pointed out the difficulty of filling the variables of the CF equation with reliable figures, as mentioned above, no exploration into the remaining variable – the production (P) variable – can be found in the literature nor a holistic assessment of all the input parameter's accuracies as described above. There is thus a gap in the literature regarding this point.

This study aimed to assess the accuracy of the carbon footprint (CF) component of the EF calculations from the standpoint of the reliability of the data used for the P variable of the CF equation in combination with the recognized uncertainties in AFCS and OSFr. Two previous studies have shown the importance of data accuracy in EF calculations and how inaccuracy in a single data point can have a big impact on the results (Jóhannesson et al., 2018; Jóhannesson et al., 2019) at least in relation to the fisheries component of EF. Since CF is responsible for about 50% of the global total EF it is important to ascertain if similar inaccuracies and sensitivity are found within the data used for the P variable of the CF equation.

In the study, the input data (P) used for the CF was traced to its origins and its accuracy assessed and sensitivity tests were made to assess the impact on the final results. In addition, calculations were made incorporating the standard error for AFCS from Mancini et al., 2016 and the upper and lower levels of uncertainty of OSFr from Khatiwala et al., 2009.

To focus the research, Iceland was used as a case study to highlight issues pertaining to EF's national and global CF accounting. Iceland makes an interesting case in this respect since very little fossil fuel is used for space heating and electricity generation due to the harnessing of local renewable resources such as water and geothermal heat. 99.9% of all electricity production in the country is powered by renewable energy and about 96% of space heating (Orkustofnun, 2018a,b).

The results show that estimates play a major role in GFN's CF calculations mainly due to the use of IPCC default emission factors. Further, activity data from international databanks rarely match locally sourced data. The change in CF under the data scenarios created range from a 42% decrease in CF to a 147% increase. Relevant caveats regarding estimations in CF calculations are found lacking in GFN's dissemination of results.

The next section of this paper briefly explains the standard CF method and how the study was conducted, section 3 presents the results, section 4 provides a discussion about the results and section 5 lays out conclusions and considerations.

2. Research method and design

2.1. The Ecological Footprint

The Ecological Footprint aims to measure nature's annual resource production – referred to as biocapacity (BC) – and measure that against human consumption of those natural resources – named footprint of consumption. The unit of measure is primary production (PP), which is then converted into productivity-adjusted hectares called global hectares (gha). The method's creators William Rees and Mathis Wackernagel (1996, p. 227) say EF attempts to answer the question:

"How large an area of productive land is needed to sustain a defined population indefinitely, wherever on earth that land is located?"

The methodology defines six land types: cropland, grazing land, forests, sea and water, built-up land and carbon uptake land, as the source of the resources humans can utilize. EF is thus based on the idea that all human consumption can be traced to the relevant land type (including sea and water) providing the natural resources needed to produce the goods and services being consumed (Wackernagel et al., 2002).

To convert the size of the areas from hectares into gha, two coefficients are used to account for the difference in productivity between the land types – equivalence factor (EQF) – as well as the difference in productivity between the same land types in different countries – yield factor (YF).

The general calculation for EF then utilizes these two coefficients to normalize the ratio of production/consumption (P) and the national yield (Y_N) for the product in question as:

$$EF = \frac{P}{Y_N} * YF * EQF \qquad (1)$$

Once the production footprints have been found in this manner for all land types, import/export footprints are calculated using the same methods and added/subtracted to/from the relevant land type production footprint to form the footprint of consumption. These consumption footprints are then added up to form the final EF. EF is then compared to the BC, which is found by the area used for utilization of a given land type multiplied by the YF and EQF.

$$BC = A * YF * EQF \qquad (2)$$

here A is the area available for the production of the goods of a given land type and YF and EQF are the yield and equivalence factors for the land type.

2.2. Carbon footprint according to the EF

CF within EF differs from the most common use of the term CF, where direct CO2 emissions, or CO2 equivalents, are being measured – as opposed to the area of land required to sequester a given amount of CO2 as done in EF calculations. CF as a part of an EF account is thus defined as:

> *"…the area of forest land required to sequester anthropogenic carbon dioxide emissions."* (Lin et al., 2018a).

Mancini et al., 2016 extend this definition to:

> *"…the regenerative forest capacity required to sequester the anthropogenic carbon dioxide emissions that is* (sic) *absorbed by oceans*"

All flows of supply chains and their embodied land use are accounted for in physical units in EF and therefore its CF component, and as such the accounts fall under the category of material flow analysis as opposed to input–output analysis based on monetary flows (Henders and Ostwald, 2014).

The equation for CF is:

$$CF = \frac{P_C * (1 - OSFr)}{Y} * EQF \qquad (3)$$

here the production variable denotes the "production" of CO2 – so P_C is CO2 emissions, OSFr is ocean sequestration fraction (the amount of CO2 sequestered by earth's oceans) and Y is average global forest sequestration rate.

Only forests are taken into account for terrestrial sequestration since: "*…most terrestrial carbon uptake in the biosphere occurs in forests, and to avoid overestimations…"* (Borucke et al., 2013).

The data used for the CF calculations are mainly taken from the International Energy Agency (IEA) and UN Commodity Trade Statistics Database (Comtrade). Further insights into the data used for the accounts can be found in the Supplementary information (SI) with this study.

A more detailed description of the CF methodology can be found in the literature such as the 2016 study by Mancini et al. as well as the multiple studies explaining the standard calculation method of the EF as defined by GFN (Monfreda et al., 2004, Wackernagel et al., 2006; Kitzes et al., 2006, Kitzes et al., 2007, Ewing et al., 2008, Ewing et al., 2010; Borucke et al., 2013; Lin et al., 2018a,b).

2.3. The object and sources of the assessment

We concentrate on the P component of the CF calculation method as described above, and particularly on the input data utilized when following the standard EF method.

Key documents used for this assessment were, from GFN: *Working Guidebook to the National Footprint Accounts, 2016 Edition (updated 2018)* (Lin et al., 2018a) and the *National Footprint Accounts* (NFA) for Iceland (data year 2014 – the latest one available at the time of this study) (graciously provided by GFN). From the IEA: *CO2 From Fuel Combustion – Highlights, 2015 Edition* (IEA, 2015), *Emission Factors 2018, Database Documentation* (IEA, 2018a) and *CO2 from Fuel Combustion, Database Documentation, 2018 Edition* (IEA, 2018b). From IPCC: *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (GLs 2006) (IPCC, 2006).

Where possible the data used by GFN, coming from international databases, was compared to locally sourced data in line with suggestions from GLs 2006 and Kitzes et al., 2007. Local data was collected from the Icelandic Environment Agency (EA), the Icelandic National

Table 1
GFN and local data sources.

Data	Worksheet	Source	Local source
Production emissions	fossil_efp	IEA	EA (NIR 2018)
Fugitive emissions	other_co2_efp	IEA	EA (NIR 2018)
Industrial processes emissions	other_co2_efp	IEA	EA (NIR 2018)
Imports/exports	carbon_efi_efe	Comtrade	Statistics Icel.
Embodied energy	carbon_efi_efe	Ecoinvent etc.	–
International transport emissions	Int_transport	IEA	EA (NIR 2018)
Electricity imports	electricity_trade	IEA	–
Electricity exports	electricity_trade	IEA	–
Electricity production	electricity_trade	IEA	NEA
Carbon intensity of imports	carbon_intensity_n	Internal calc.	–
Domestic total primary energy supply	carbon_intensity_n	IEA	NEA
Carbon intensity of exports	carbon_intensity_n	Internal calc.	–
National electricity carbon intensity	cnst_carbon	IEA	–
Regional electricity carbon intensity	cnst_carbon	IEA	–
World primary energy carbon intensity	cnst_carbon	IEA	–
Total primary energy supply	cnst_carbon	IEA	NEA

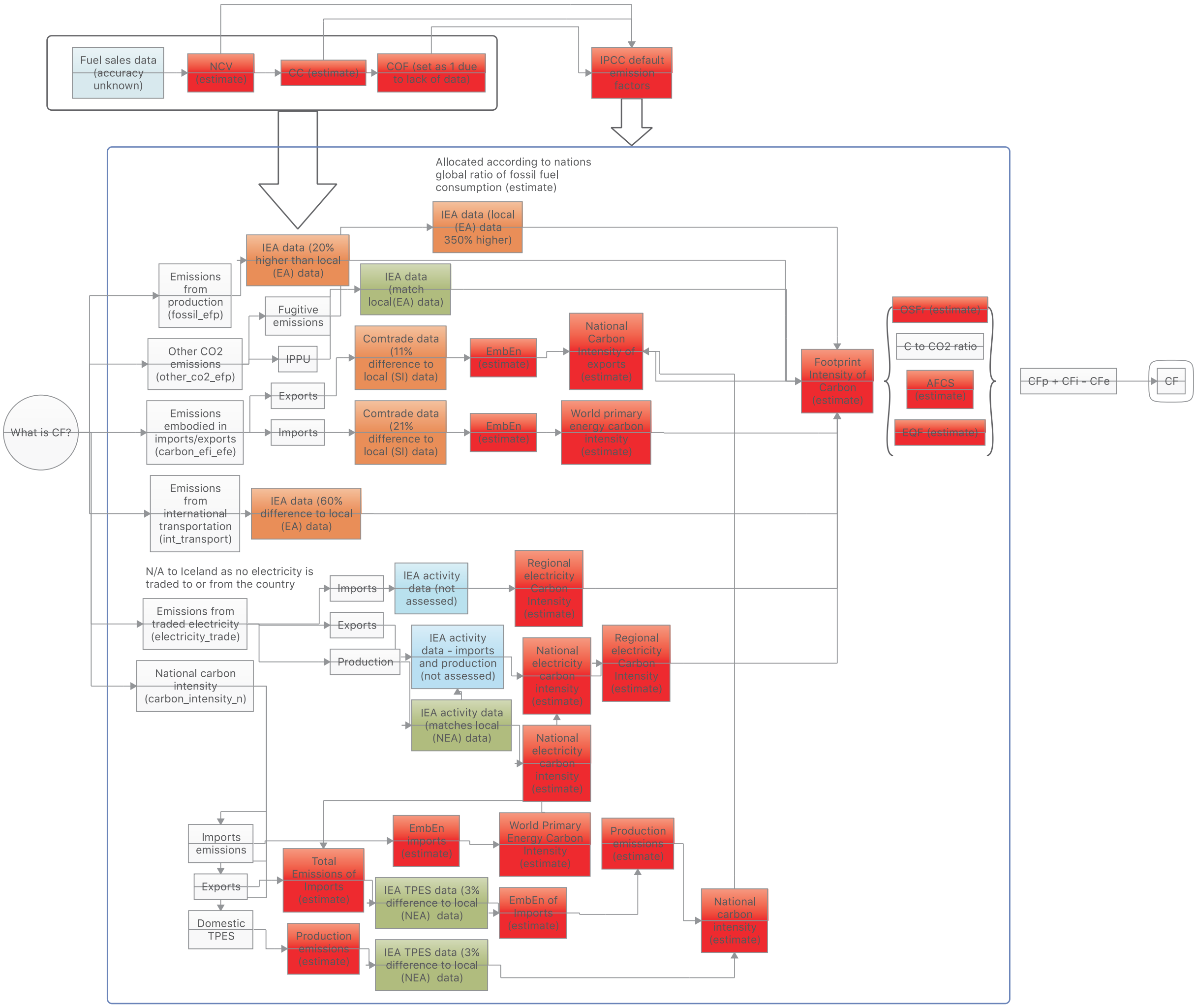

Fig. 1. Graphic illustration of CF calculations.

Energy Authority (NEA) and Statistics Iceland.

Table 1 below shows the data sources used by GFN and the local sources used for this study. Please refer to the Supplementary information (SI) for further information on the table's content.

2.4. Research design

The intention was to look for inaccuracies in the P variable of the CF equation and assess their impact on the results in relation to recognized uncertainty in the AFCS and OSFr variables.

All data was thus traced to their origins to assess their robustness and sensitivity tests were made to the original GFN data to check for unusual responses of the calculation matrix. The sensitivity testing was built around IEA's assumption that for most Annex II countries the accuracy of their data is within 5 – 10% (IEA, 2015), hence a 10% change in data was used as a general benchmark.

No assessment was made of the IEA assertion that for most Annex II countries the accuracy of the data is within 5–10%.

Tests were intended to give an idea of the possible range of outcomes given the uncertainty associated with the data. The 10% error margin of the P variable assumed by the IEA was used for this purpose along with the recognized uncertainty of the AFCS and OSFr variables.

The tests included:

- Using locally sourced data where they differed from the GFN data
- Imposing a flat increase of 10% of all data points
- Imposing a flat decrease of 10% of all data points
- Imposing a flat 10% increase in all data except exports which were decreased by 10%
- Imposing a flat 10% decrease in all data except exports which were increased by 10%
- Imposing a 10% decrease in the embodied energy for traded fish and increasing the energy embodied in traded alloys, plus a 10% increase in imports in these categories as well as a 10% decrease in their exports
- Incorporating the AFCS standard error from Mancini et al. (2016) into the matrix
- Incorporating the upper and lower limits of OSFr from Khatiwala et al. (2009)
- Calculating the CF with the upper and lower limits of the AFCS from Mancini et al. (2016) and of the OSFr from Khatiwala et al. (2009) with positively and negatively influencing local data
- Identifying the upper and lower limits of the error margin based on these tests

Sensitivity testing was focused on the P variable of the CF equation, but further to that test were also made to assess the impact of the standard error of AFCS from Mancini et al., 2016, on the results, as well as the upper (35%) and lower limits (20%) of Khatiwala et al., 2009 estimate of OSFr and the upper and lower limits of the error margin under the scenarios created.

3. Results

The study finds that the upper and lower limits of the case scenarios created from local data, AFCS standard error (Mancini et al., 2016) and OSFr upper and lower limits (Khatiwala et al., 2009) results in a change to CF from a 42% decrease for the lower limit to a 147% increase for the upper.

Further, of all the data points in the CF calculations for Iceland only two – *industrial processes and product use* (IPPU) and *electricity production* – match locally sourced data. Other data points show a discrepancy when compared with local data or are estimations. IPCC's default emission factors play a key role in the estimation of most of the estimated data points.

This discrepancy between the IEA data used by the GFN and the locally sourced data ranges between 3 and 350%. The greatest difference is for fugitive emissions, 350%. Only totals of traded goods (in mass units) were assessed, as data sets were incompatible. Totals of traded goods showed a 21% difference in imports and a 11% difference in exports, with local data being higher.

Figure 1 is a graphic illustration of how the CF calculations are set up, estimated data points and the percentage difference between GFN (IEA) data and local data. Green indicates data points that are within a 10% difference between GFN data and local data, orange indicates data discrepancies above 10% and red indicates estimated data points. Descriptive boxes are left uncoloured and blue indicates data not assessed. The blue frame denotes the scope of the study (EQF is outside the scope of the study but for clarity's sake is inside the blue frame since it is a part of the *footprint intensity of carbon* in the calculation matrix).

Incorporating local data into the GFN matrix yields a 13% increase in the Icelandic CF. This is regardless of the fact that some of the local figures raise the total CF (fugitive emissions (3%), traded goods (11%) and bunker fuels (4%)) while others lower it (production emissions (–3%)) – effectively working against a change in the final CF. The local data are all based on the same IPCC default emission factors as the data used by GFN.

A flat 10% increase or decrease in all data yields a 14% and −13% difference in CF, respectively. Since a rise in export values will lower the CF a flat increase over the whole accounts will to some extent be balanced out. This can be seen when a flat 10% increase is incorporated into the accounts with an equal 10% decrease in export data. This results in a 37% increase in total CF.

Fig. 2, below, shows how CF is affected by a 10% increase in key input data points – one at a time. International trade is highlighted as having the most impact on total CF.

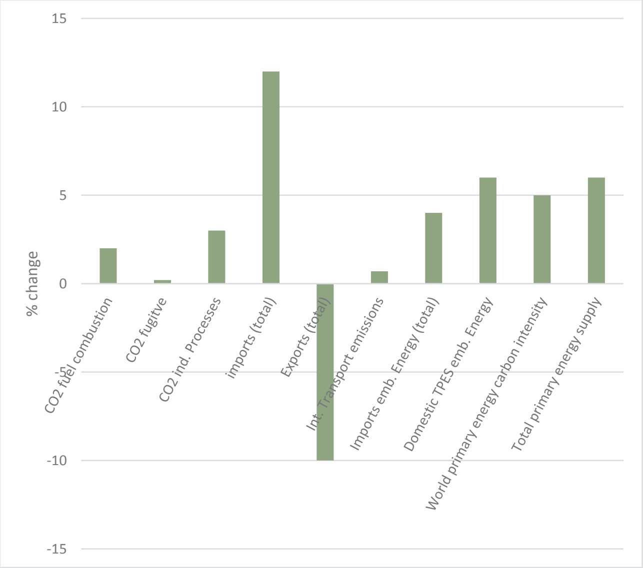

Fig. 2. Effects on CF by a 10% change in key input data points.

Only making 10% changes to the embodied energy in the main traded goods, lower for the main export goods (fish – listed under SITC 1 as *Fish, fresh, chilled or frozen, Fish, salted, dried or smoked, Crustacea & mollusks, fresh, chilled, salted, dried, Meat & fish meal, unfit for human consumption* – and aluminium alloys – listed under SITC 1 as *Aluminium and aluminium alloys, unwrought, Aluminium and aluminium alloys, worked, other ferro alloys* Hagstofa Íslands, 2019 and higher for the main imports (bauxite – listed under SITC 1 as *Other inorganic bases and metallic oxides* – and electric gadgets and machines – listed under SITC 1 as *Electrical machinery and apparatus, nes* Hagstofa Íslands, 2019) raises the total CF by 16%.

AFCS was also changed according to the standard error given by Mancini et al., 2016. Lowering the AFCS by the standard error yielded a 96% increase in CF.

Table 2 below shows how the sensitivity tests affect the CF and its different categories.

Table 2
Sensitivity test results.

	Prod.	Imp.	Exp.	CF	% Change
Baseline	3,86	7,51	5,49	5,87	–
Local data	3,61	9,60	6,58	6,63	13
Flat 10% increase	4,24	9,90	7,48	6,67	14
Flat 10% decrease	3,47	5,54	3,92	5,09	−13
10% increase + 10% decrease in exports	4,24	9,90	6,12	8,02	37
10% decrease + 10% increase in exports	3,47	5,54	4,80	4,22	−28
Fish and alloy 10% change	3,86	8,00	5,06	6,80	16
AFCS + standard error	2,56	5,11	3,64	4,03	−31
AFCS – standard error	7,82	14,82	11,14	11,51	96
OSFr – lower limit (20%)	4,39	8,49	6,25	6,63	13
OSFr – upper limit (35%)	3,57	6,94	5,08	5,43	−7
AFCS-SE + OSFr (20%) + higher local data	9,25	17,92	12,68	14,50	147
AFCS + SE + OSFr (35%) + lower local data	2,11	4,61	3,29	3,43	42

Further info on how the various data points are estimated can be found in the accompanying Supplementary information (SI).

Fig. 3 shows the range of percentage change in CF under the different scenarios created.

4. Discussion

The aim of this study was to assess the accuracy of the data used for calculations of the P variable of the CF equation of EF calculations and reviewing the combined impact of any inaccuracies with the recognized uncertainties in the AFCS and OSFr variables. This was done by tracing the data used for each data point to its origins and testing the sensitivity of the accounts according to the uncertainty involved.

The results suggest that the data used for the CF of EF is lacking in accuracy and the impact on the results ranges from −42% to +147% in the Icelandic case. Although every country is an individual case with its own set of particulars, there is no obvious reason to believe that similar uncertainties do not apply to other national accounts as well as global estimates. This is, to a degree, in line with van den Bergh and Grazi's (2013) conclusion about what they call the *false concreteness* of EF – mainly due to CF – although for different reasons. While van den Bergh and Grazi used the term for the metaphoric use of land as a metric, here, the lack of concreteness is a direct result of the uncertainty of the data.

CF as a part of EF falls under the umbrella of sustainability indicators. As the name suggests these are meant to give an indication of a situation or a state of affairs and therefore a 100% accuracy is not to be expected. The extent of inaccuracy within the CF is all the same a concern, especially since – as shown by Jóhannesson et al. (2019) –

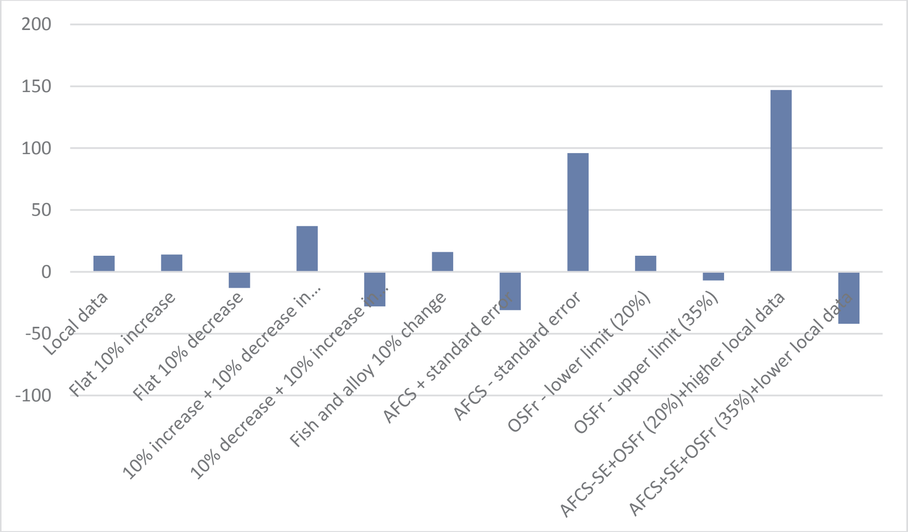

Fig. 3. Percentage change to CF under different scenarios of data variance.

small changes to one data point within the EF calculation matrix can have a big impact on the final result. When almost no data point in the whole calculation can be considered free from estimation or inaccuracy of some kind, the result can be considered just one of a hundred or a thousand possible results.

It should be stated that this lack of concreteness – or accuracy – is not limited to EF but applies, to some degree at least, to any emissions calculation based on the IPCC default emission factors since they are based on various estimates and averages (Kainou, 2005) as further detailed in the Supplementary information**.** Added to this is uncertainty that rises from the discrepancy between locally collected data and international databanks – up 350% difference.

This raises some important questions. One is about the accuracy of the data behind the UNFCCC national reports. Although outside the scope of this study it warrants a brief mention due to its close relation to the research subject. GHG emission estimates are based on two things: Activity data (what has been done by humans) and the amount of GHGs released by that activity (emission factor). Neither variable is straightforward and requires multiple factors of data gathering and, often, estimations. As with EFs CF, it is very difficult to assess the accuracy of such estimations especially when they have reached a larger scale such as national or even global levels. The most common quality indicator used is the *confidence interval* – as suggested by GLs 2006. Birigazzi et al. (2019) criticize these guidelines and question the validity of using a confidence interval (usually between 90 and 95% in this context) as a quality indicator for an estimate – such as of emission factors or activity data – without any information on estimation procedures (sampling size, measurement protocols, quality control procedures etc.).

Discussing the issue of estimates in regional carbon budgeting, Enting et al. (2012) states:

> "…uncertainties are both hard to calculate and hard to interpret."

Enting goes on to quote Raupach et al. (2005), who said:

> "*An essential commonality is that for all model-data synthesis problems, both nonsequential and sequential, data uncertainties are as important as data values themselves and have a comparable role in determining the outcome*"

Considering what is arguably the most recognized source of anthropocentric GHGs, emissions from road transportation, there are a variety of factors that come into play affecting the emissions from every vehicle. These are factors to do with the vehicle, such as engine capacity, power and size, fuel type, vintage, speed-driven at, acceleration/deceleration, vehicle maintenance, engine type etc. (Prakash and Habib, 2018a), road-related factors such as road surface condition, gradient, pavement type etc. and environmental factors such as relative humidity, temperature etc. (Demir et al., 2011). It is not hard to see the need for averages and estimations in an assessment of any given fleet of cars at any given time.

These averages and estimates are crystallized in the IPCC default emission factors. The emission factors are based on estimates of net calorific value (NCV), carbon content (CC) and carbon oxidation factor (COF) of different fuels. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2006 GLs) (IPCC, 2006) base their estimates of NCV, CEF and COF on *Revision of default Net Calorific Value, Carbon Content Factor and Carbon Oxidization Factor for various fuels in 2006 IPCC GHG Inventory Guideline* a report prepared, seemingly, for the IPCC, by Kazunari Kainou (2005). The report's statistical analysis is in turn based on data from the UNFCCC, IPCC and the IEA (IPCC, 2006). The report's author also references a Japanese government body, an industry foundation, the author's own statistics manual and one scientific article (Yoshioka, 1983). No outside verification of these calculations can be found in the literature – yet these are the foundations of global emissions estimation – the IPCC default emission factors.

As with EFs CF, the more elaborate the models we build on top of this kind of uncertainty the less likely we are to reach realistic results.

In a recent study, Prakash and Habib (2018b) lowered the uncertainty in CO2 emission estimates for road transportation in India from 106% in previous studies (Baidya and Borken-Kleefeld, 2009; Sadavarte and Venkataraman, 2014) to 32% by using emission factors from field measurements as opposed to dynamometers or emission models. Shan et al. (2016) found that out of 2368 studies on carbon emissions in China 99% used default emission factors from IPCC or the Chinese public sector and only 1% of studies used emission factors from field measurements and experiments. They further showed that those emission factors can differ by up to 40% and that official defaults were frequently higher than field measurements. Liu et al. (2015) reached similar conclusions with the defaults showing 40% and 45% higher emissions for coal and cement production, respectively, in China, than their results where they used clinker production data, rather than the default clinker-to-cement ratio. Similar sentiments are echoed in Shen et al., 2014; Kim et al., 2016; Kim et al., 2017; Aliyu et al., 2019 and Cho et al., 2019.

This brings us to the second component of van den Bergh and Grazi's (2013) "false concreteness" concept. That is the notion of falsehood. If these uncertainties were always clearly stated as these methods and results were discussed this would not be a problem.

Unfortunately, this is not the case. This is the core of the problem. A method becomes accepted; caveats are supposedly well known and not worth repeating, resulting in estimates being reported as concrete data.

This is clearly seen in the GFN 2018 Guidebook. An important reference for the CF calculations is the IEA. In the IEA document *The IEA estimates of CO2 emissions from fuel combustion* it is frequently stated that these are estimates of CO2 emissions, as clearly seen in the title. This is not so clear in the GFN 2018 guidebook. Pages 12 and 13 of the guidebook briefly explain the methodology and data used in the calculation (estimation) of CF and the use of terminology does not indicate that any estimation is taking place. Here is how the IEA data use is explained:

> *"The International Energy Agency (IEA) tracks carbon dioxide emissions from fossil fuel combustion across 45 different economic sectors. These data are used in NFA 2018 to calculate the carbon Footprint of production. If IEA data are not available for the country and year in question, an estimate from the Carbon Dioxide Information Analysis Centre is used (Boden et al., 2013)."*

Anyone who reads this and is not familiar with the provisos given in *The IEA estimates of CO2 emissions from fuel combustion* might think that the IEA data is *accurate* and only where these data are not available will an *estimate* from the Carbon Dioxide Information Analysis Center (CDIAC) be used.

Further examples of this lack of clarity within the GFN Guidebook text include:

> "The IEA also publishes the total world emissions in international transport in the form of International Aviation bunker fuel…"
> "The carbon Footprint represents the area of forest land required to sequester anthropogenic carbon dioxide emissions."
> "The **NFA 2018** workbook calculates the Footprint of carbon dioxide emissions using several parameters…"

While the terms calculations, allocation, attribution, distribution, derivation and representation are used – and some repeatedly – the term estimation is only used once apart from the example above regarding the Carbon Dioxide Information Analysis Center data. This is when referring to embodied energy in traded goods:

> "Embodied carbon emissions in traded goods are calculated by multiplying estimated embodied energy figures by the world average carbon intensity for primary energy production in case of imports…"

It could be argued that all the above statements – and more – should be tempered with a proviso.

The lack of caveats has spurred what is likely the most serious criticism of EF from Giampietro and Saltelli (2014a) (p.619), who claimed that EF might be:

> *"…vulnerable to the critique of Pseudo-Science as defined by Funtowicz and Ravetz (1990, 1994) when discussing quality criteria for science used in support to policy: "[pseudo-science is] where uncertainties in inputs must be suppressed lest outputs become indeterminate."*

This failure to caveat results and methods is a serious concern and it is where environmental scientists can't let their good intentions get the better of them. Most environmental scientists are likely drawn to the field due to an affinity for the natural world. This can be a source of bias. This bias may explain such omissions of caveats. The reasoning being that the issues are so great that scientific accuracy and good practice must take second place to awareness-raising. This is dangerous. Scientists have every right to be activists – but only in their spare time. Science needs to be practiced with a steady heart and a cool mind.

Possibly it is at this interface between science and activism that these problems of EF originate. The science of EF is too intrinsically interwoven with the activist/promotional/marketing activities of GFN. In the 2009 article *A research agenda for improving national Ecological Footprint accounts,* Kitzes et al. (2009) (p.2003), touch on this issue by underlining the importance of how future development of the EF must take into account the fact that EF is already being used (as an accounting tool on the free market presumably) and therefore cannot be approached as *"…purely an academic exercise…"*. It should be clear that these are two separate issues for two separate fields. One is the concern of science – making the accounts as robust as possible, the other the concern of the after-service unit of a product – making methodological improvements functional for those already using the accounts. The latter should never affect the former. In reality, it would likely be very difficult for GFN to incorporate a change in the methodology that would change the concept in a way that would confuse or confound its current users in a major way. One such change would be to drop the CF from the accounts due to a lack of accuracy of the available data. This would mean the global EF would be within the limits of global biocapacity and the need to continue measuring EF would be seriously undermined. The same likely holds for other similar entities that attempt to mix scientific development with the promotion of an ideology.

Arguably the best thing for further development of EF would be for GFN to completely separate the research activities from the promotional/services activities. This may already be on the horizon with a new alliance between GFN and York University in Canada (York, 2019) http://footprint.info.yorku.ca/.

The attention that the EF gets and its approachability makes it very special. The idea to focus on the productivity of nature and compare with human consumption is arguably the key factor to this approachability and EF's success in bridging academia, policymakers, media and the public. This is, therefore, a precious idea. Has it been implemented in the correct way? Can it be implemented in a way that produces "accurate" results? Do we have the data? Do we have the resources to collect the data? Is it worth the time, energy and resources that it will take to get the data to an acceptable level of quality? These are all questions up for debate.

5. Conclusions

EF is arguably one of the most successful concepts to come out of the field of environmental science in terms of raising public awareness of the pressures that human endeavour is putting on the natural world. This makes the EF a very special thing.

To state categorically that the Ecological Footprint of humanity – or a nation, or any other subset of individuals – is any given number, is inherently misleading and false. The uncertainties in the data behind the carbon footprint – responsible for over half of the global footprint according to the method – are too great. The fact that these numbers are more often than not stated as if they were absolute and concrete, is worrisome.

The reason for results missing caveats may, possibly, be traced to the fact that the entity largely responsible for the promotion of the concept around the world is also a leading research unit on the methodology. This runs the risk of lines blurring between scientific endeavour on the one hand and environmental activism and the practical needs of an institution, such as an NGO, on the other – which may lead to caveats being downplayed in the dissemination of results.

The study also raises the question if this points to a larger problem of similar inaccuracies in GHG accounting in general, since most are based on the same estimated data from large institutions such as the IPCC and IEA – and, further, if other institutions that attempt to encompass both the realm of science and that of politics – such as the IPCC – don't face the same dangers of bias as GFN?

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CRediT authorship contribution statement

Sigurður E. Jóhannesson: Conceptualization, Validation, Formal analysis, Investigation, Writing - original draft, Project administration. **Jukka Heinonen:** Resources, Writing - review & editing, Supervision, Funding acquisition. **Brynhildur Davíðsdóttir:** Resources, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105983.

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Supporting information

DATA ACCURACY IN ECOLOGICAL FOOTPRINT'S CARBON FOOTPRINT

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Table of contents:

Data origins and calculations in the GFN Workbook CF component

Following is a description of the origins of data used in the Ecological Footprint (EF) carbon footprint (CF) calculations. Headings indicate the name of the tab in the Global Footprint Network (GFN) workbook and subheadings the various columns or rows as required for further explanations.

fossil_efp

The data used for CO2 fuel emissions used for the GFN workbook comes from the International Energy Agency (IEA). The IEA data is in accordance with the IPCCs emissions from fuel combustion Source/Sink Category 1 Fuel Combustion Activities and those from fuel combustion that may be re-allocated to Source/Sink Category 2 Industrial Processes and Product Use – covering CO2 emissions only.

The fuel sales figures used by the IEA come from the Icelandic National Energy Authority (NEA). These are converted into energy units with average net calorific value (NCV). These data are then multiplied by the relevant emission factors taken from IPCC 2006 GLs default emission factors.

The equation for the emissions is:

$$CO2 = AD * NCV * CC * COF$$

Where CO2 stands for emissions, AD for activity data (e.g. sales figures), NCV for net calorific value, CC for carbon content and COF for carbon oxidation factor.

All variables of the equation are estimates – as seen below:

Fuel sales figures

Iceland is not an official member of the IEA but the National Energy Authority voluntarily sends them sales figures for oil in the country (NIR, 2018). Sales data collected by the NEA from companies selling and distributing oil in Iceland. The accuracy of these data is hard to assess. According to NEA staff there is frequent communication between the NEA and the oil companies regarding various issues with the data that the NEA find. These can be typos, discrepancies between years, goods accounted for in the wrong category etc. (Oddsdóttir, 2019). The sales figures are rounded up by IEA, which for a small economy such as Iceland can have a significant impact on the data percentage wise (NIR, 2018). Fuel sales figures are thus not strictly estimates but their accuracy is uncertain.

NCVs

Sales figures are given in physical units (tonnes or cubic meters) and need to be converted into energy units to estimate emissions. For this net calorific values for the different fuel types are used. How this is done is not made altogether clear in the IEA document *CO2 Emissions From Fuel Combustion: Database Documentation (2018 Edition).* On page 59 it says:

> "*The IEA CO2 emissions from fuel combustion estimates are based on the IEA energy balances, computed using time-varying country-specific NCVs.*"

On page 55 of the same document it is stated:

> "*To transform fuel consumption data from physical units to energy units, the IEA uses an average net calorific value (NCV) for each secondary oil product. These NCVs are region-specific and constant over time. Country-specific NCVs that can vary over time are used for NGL, refinery feedstocks and additives. Crude oil NCVs are further split into production, imports, exports and average. Different coal types have specific NCVs for production, imports, exports, inputs to main activity power plants and coal used in coke ovens, blast furnaces and industry, and can vary over time for each country.*
>
> *Country experts may have more detailed data on calorific values available when calculating the energy content of the fuels. This in turn could produce different values than those of the IEA.*"

It is further unclear if this is some confusion due to a change in methodology between the 1996 version of the IPCC Guidelines (GLs) and the 2006 version. On page 58 it says:

> *"In the 1996 GLs, country-specific net calorific values were given for primary oil (crude oil and NGL[1]), for primary coal and for a few secondary coal products. These NCVs were based on the average 1990 values of the 1993 edition of the IEA Energy Balances.*
>
> *In the 2006 GLs, those country-specific NCVs were removed, and one default is provided for each fuel (with upper and lower limits, as done for the carbon content)."*

From this it seems unclear if the average NCV is used or if it is country-specific NCVs from the 1996 methodology or even how the NCVs are estimated in general. In any case it is clear that these data are estimates.[2]

Carbon content (carbon emission factor)

Carbon content reflects the amount of carbon per unit of a given fuel. This is not a constant and can "…vary considerably for some fuels…" (IEA, 2018). The IEA uses the 2006 GLs default values for all fuel types. The 2006 GLs default emission factors are based on: *"…a statistical analysis of available data on fuel characteristics."* (IPCC, 2006). No references are given for the available data.

Carbon oxidation factors

During combustion not all carbon content in fuels gets oxidized. In 1996 GLs this was estimated by a carbon oxidation factor. According to the IEA: *"…in most instances, emissions inventory compilers has no "real" information as to whether this correction was actually applicable."* (IEA, 2018). For this reason, the 2006 GLs assumes all carbon is oxidized during the combustion process. This component of the equation therefore equals 1, which effectively turns CC into a carbon emission factor.

Other_co2_efp

Other CO2 covers CO2 emissions from oil and gas flaring (fugitive emissions) and non-fuel combustion emissions from industrial processes. The data are taken from IEA.

Figures for oil and gas flaring are estimated in accordance to a nations share in global fossil fuel consumption. The figure given by IEA is 0.04 Mt CO2 yr^{-1}. The Icelandic EA NIR figure is 0.18, 350% higher.

The figure for industrial processes and product use (IPPU) is the only data point in the CF accounts for Iceland that accurately matches local data. The accounts use the figure 1,7 Mt CO2 and the EA's NIR gives 1654 t CO2.

carbon_efi_efe

For estimating CF of traded goods EF uses the standard international trade classification (SITC) 1 from The United Nations Commodity Trade Statistics Database (UN Comtrade).[3] No matching data could be located within the Statistics Iceland database (Gunnarson, 2019). Statistics Iceland present their data in a large number of tables which include a range of different categories depending on the intended use of the data. The two tables identified that come closest to presenting the same data as GFN workbook are found in two different places, have slightly different names[4] but present the same data. The GFN data is more detailed than these (e.g. 12 different categories for meat products while the Statistics Iceland data only includes 4 - as a random example). The difference in total amount of traded goods between

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[1] Natural Gas Liquids

[2] An explanation on how the default values are estimated can be found in chapter 1 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

[3] UN Comtrade disclaimer on limitation and coverage of its data states: "Whenever trade data are received from the national authorities, they are standardized by the UN Statistics Division and then added to UN Comtrade." Further it states: "When data are converted from a more recent to an older classification it may occur that some of the converted commodity codes contain more (or less) products than what is implied by the official commodity heading. No adjustments are made for these cases."

[4] *Innflutningur eftir vöruflokkum SITC Rev. 4, 1999-2015* and *Innflutningur eftir vöruflokkum SITC 3 Rev. 4, 2010 – 2017. Útflutningur eftir vöruflokkum SITC 3 Rev. 4, 2010-2017*

the two sets of data is: For total imported goods 21% - 4.528.463 tonnes according to Statistics Iceland but 3.601.188 tonnes according to the NFA, for exports 11% - 2.145.391 tonnes in SI data and 1.943.988 tonnes in the GFN data.

EmbEn

The embodied energy in traded goods is estimated using data from several different sources; Ecoinvent Database, Hammond and Jones (2008), Thormark (2002), Interfacultaire Vakgroep Energie en Milieukunde Energy Analysis Program (IVEM 1999), and a collection of life cycle analysis (LCA) data from the Stockholm Environment Institute at York University (Lin et al, 2018). This is an attempt to assess how much energy has been used for the production and waste disposal of the various different products traded.

LCA suffer from multiple uncertainties and ambiguities as is well reported in the literature (Jung et al, 2013; Hendrickson et al, 2006).

CO2 intensities

For imported goods estimates of world average carbon intensities are used.

For exports the estimate is taken from carbon_intensity_n (see below).

Int_transport

International transport emissions (bunker fuels), which are emissions associated with overseas flights and shipping, are published by the IEA, where they are "…*allocated to countries according to their respective domestic fossil fuel combustion by the proportion of national to world imports.*" (Lin et al, 2018). This is the data used by GFN and is given as 0.38 Mt CO2 in 2014. The Icelandic EA's NIR, 2018 gets a 60% higher figure of 0.63 Mt. The EA estimate bunker fuels from NEA activity data.

electricity_trade

Calculations involve IEA data on traded electricity and the constants *Regional electricity carbon intensity* and *National electricity carbon intensity*. No electricity is traded to or from Iceland, so no data is available, neither locally nor from IEA. *Regional electricity carbon intensity* and *National electricity carbon intensity* are estimates from IEA as indicated under cnst_carbon below. Data on produced electricity derives from IEA and matches locally sourced data from NEA.

Carbon_intensity_n

To find the carbon intensity of exports, first the total CO2 of imports is found by multiplying the total estimated embodied energy of imports (see carbon_efi_efe above) with the *World Primary Energy Carbon Intensity* estimate (see cnst_carbon below). Next total national primary energy supply is taken from the IEA database. The GFN workbook has this figure at 245,555,820 GJ. The NEA gives 237,936,999 GJ (OS, 2015) or about 3% lower. Then carbon intensity of exports is estimated as the ratio of the sum of the total emissions for TPES (taken from fossil_efp) and imports and the sum of total embodied energy of imports and TPES. The embodied energy of exports is taken from carbon_efi_efe and the carbon intensity of TPES is the total emissions of production divided by the embodied energy.

Cnst_carbon

The following constants are used for various calculations within the CF matrix.

C to CO2 ratio

Shows the ratio between carbon and carbon dioxide (27%).

Carbon Sequestration Factor

The estimated amount of carbon sequestered by natural systems. GFN only uses the estimated capacity of world average forests for this and sets the rate at 0.73 tonnes carbon per hectare per year.

Ocean uptake fraction

GFN uses Khatiwala et al, 2009 as the main source for the fraction of CO2 sequestration by the ocean, currently estimated at 30%.

National Electricity Carbon Intensity

Taken directly from IEA CO2 emissions estimates.

Regional Electricity Carbon Intensity

Taken directly from IEA CO2 emissions estimates.

World primary energy carbon intensity

Taken directly from IEA CO2 emissions estimates.

Footprint Intensity of Carbon

Footprint intensity of carbon is given as 0,338 [gha (t CO2 (yr-1))-1] and is calculated internally by multiplying C to CO2 ratio * (1 – OSFr) * AFCS^{-1} * EQF.

Reference:

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