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Abstract: Consumption-based accounting has been used to understand the resource and environmental pressures associated with the consumption of goods and services. Capture fisheries have significant economic, cultural, and environmental importance, yet relatively limited attention has been given to understanding their consumption-linked pressures. Where products of marine and inland fisheries are accounted for, they are typically done so within the context of 'material' footprints or within life cycle assessment-based studies which draw more attention to resource efficiency or pollution-related aspects of fisheries than the species or ecosystem-linked consequences of the extraction process itself. However, the sustainability of fisheries products is highly dependent on the catch method, location, and species targeted. To date, these have been missing from consumption-based accounts. Here, a collation of species-specific information comprising vulnerability and environmental pressure associated with capture is provided, which is then linked to a global multi-regional input-output model to - for the first time - create a dedicated consumption-based time-series for fisheries. Whilst the aggregate footprint of global capture fisheries has remained stable in recent decades, our results demonstrate that at national or regional scales different trends in consumption exist. Importantly, there have been significant shifts in the composition of catch within these consumption accounts, which have potential implications for the sustainability of underpinning supply chains. This paper draws attention to the fact that material efficiency perspectives are insufficient in the assessment of pressures on the marine environment driven by consumption of fisheries products, and - whilst challenges remain - there is a growing abundance of information and development of methods that could potentially be utilised to overcome gaps in the future.

Cover Letter

19/11/2018

Dear Editor,

Please find enclosed our revised manuscript, entitled "Improving consumption based accounting for global capture fisheries", which we would be grateful if you would consider for publication as an original article in the Journal of Cleaner Production. This article is submitted as part of the JCP edition (VSI: PRINCE) that will also consider other manuscripts resulting from the Swedish EPA-funded 'Policy Relevant Indicators for Consumption and the Environment' (PRINCE) project.

We have provided what we believe to be a thorough and comprehensive response to the reviewer, which includes edits to many parts of the paper. With particular reference to the reviewer's call for a more detailed comparison between the results of our paper and other studies, we feel that this would only be warranted within an exhaustive methodological comparison due to the complexity of interpreting results driven by the variety of methods employed across these studies. This is something that would necessitate a meta-analysis type study that sits outside the scope of our work.

Please note also that, in response to the previous review round, we modified our figures so that they appear in black-and-white. On reflection, we feel that the figures would be better served by appearing in colour in the online version of this manuscript and would therefore appreciate guidance from the editor/publishing team on the best way to present the figures for publication.

Also note that we re-upload one Annex file after an error was spotted in the previous data. All other data files remain unchanged from the previous submission.

I confirm that this manuscript has not been published, accepted for publication, nor under consideration for publication, in another journal. The work is original research and submission has been approved by all authors. All persons entitled to authorship have been so named. We look forward to hearing from you.

Yours sincerely,

Chris West

Reviewer #1: The authors have done a good job with the revision. After still having noted some limitations (see my detailed comments from introduction, material and methods and results) I found a lengthy discussion on caveats. I appologise if I brough up isssues you've addressed, but I also suggest that if these issues are not addressed where initially mentioned, the paper would benefit from a more structured discussion with sub-headings.

RESPONSE

We thank the reviewer for recognising the work we have conducted to improve upon the manuscript, and for another set of thorough and helpful comments on the paper. We hope that the responses to the more detailed comments below are satisfactory: in many cases we have referred to areas of the discussion where we felt that the recommendations of the reviewer were previously addressed, and we have also taken the reviewer's advice and added sub-headings within the Discussion which we feel should help the reader navigate across the sections of the Discussion that deal with the results context, limitations linked to, and recommendations for, integration of enhanced fisheries data and economic data respectively.

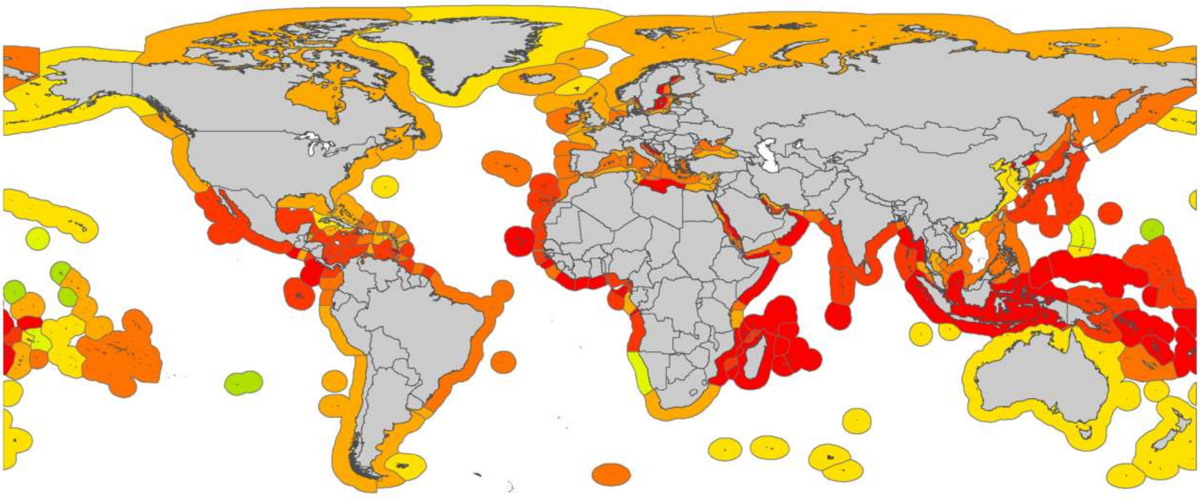
In cases where we have adopted recommendations, and where we feel that we cannot do so, we have offered an extensive justification below. In particular the reviewer requested some comparisons to other research on fisheries trade. We have modified text in sections to include further references and high-level comparisons to the references highlighted but - as per our detailed responses below - we feel that, in order to undertake a meaningful comparative analysis, a fuller meta-analysis of the various methods employed, their assumptions, and the details of their results would need to be employed, something which sits significantly outside the scope and word-limits of this paper.

Detailed comments:
Abstract: I know that this is based on your results but may be misleading (consider the fact that many just read the abstract to get an idea of the paper findings). What I specifically refer to are:
1. Location is not important to sustainability based on several LCAs. Did you really find that location significantly matters?

RESPONSE

It is likely that this comment refers to the part of the abstract that states: "However, the sustainability of fisheries products is highly dependent on the catch method, location, and species targeted."

Within our study, in contrast to historical material-footprint based consumption-based accounts, we retain information on the capture location of fish, which is then utilised in our results to explore trends over time. We would argue that the management of fisheries, and therefore their relative sustainability, <u>is</u> influenced by the location of the fishery and therefore data on location is an important consideration in studies which aim to provide insight into the pressures or impacts of consumption activity. Indeed, in our last set of revisions we included reference to the Mora et al. 2009 study which illustrates that "effective controls on exploitation rates are still lacking in vast areas of the ocean, including those beyond national jurisdiction", which highlights the potential for lower management effectiveness in many parts of the world:



We therefore feel that it is appropriate to retain the existing wording of the sentence in the abstract.

2. You state that the "aggregate footprint of global capture fisheries has remained stable in recent years". Which timeframe is referred to here? And is this really reflecting reality?

Especially if you go beyond your results? Some examples:
a.bottom trawled crustacean products (the by far most harmful product in the food system) are increasing (Anderson, S. C., Flemming, J. M., Watson, R., & Lotze, H. K. (2011). Rapid global expansion of invertebrate fisheries: trends, drivers, and ecosystem effects. PLOS one, 6(3), e14735.).
b.GHG emissions are increasing (Parker, R. W., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., & Watson, R. A. (2018). Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change, 8(4), 333.).
c.Number of stocks exploited sustainable (check e.g. FAO)?
d.Shifts in composition of catch are based on major changes in ecosystems from overexploitation (Howarth, L. M., Roberts, C. M., Thurstan, R. H., & Stewart, B. D. (2014). The unintended consequences of simplifying the sea: making the case for complexity. Fish and Fisheries, 15(4), 690-711.)

RESPONSE
In the abstract, we refer first to the 'aggregate' or total footprint which is equivalent (given our use of FAO production statistics) to the total production of capture fisheries globally. According to the FAO statistics (and as illustrated in Figure 1 of our paper) these have remained relatively stable over our 20 year time-series (1995-2014). We have changed 'years' to 'decades' in the abstract to be more specific about the time-scale referred to.

The next sentence in the abstract speaks to the reviewer's point about the 'reality' of this aggregated unchanging footprint in the context of sustainable development. Indeed, we state "our results demonstrate that at national or regional scales different trends in consumption *exist. Importantly, there have been significant shifts in the composition of catch within these consumption accounts, which have potential implications for the sustainability of underpinning supply chains". This relates clearly to the reviewer's Anderson et al. 2011 example which shows that capture of invertebrate fisheries are increasing. It is precisely the 'disaggregation' of data within our study that allows the assessment from a consumption-based perspective of the changing composition of the catch (or linked to example d. Howarth et al. 2014, for long-term trends in the 'provisioning services' that the sea provides to be assessed). Or, with reference to example b. Parker et al. 2018 - as we describe in our previous revision - advances could facilitate exploration of differential impacts on GHGs (We have modified a sentence in the paper to draw greater attention to how inclusion of such perspectives would offer a more holistic assessment of the sustainability of fisheries: "They could also facilitate a broader assessment of the sustainability of fisheries, via the inclusion of more advanced methods of assessing pressure and impact linked to fisheries consumption, including estimating the fishing effort exerted across fisheries, more detailed vulnerability assessments (accounting for vulnerability of species beyond an assessment of life-history characteristics; Pinsky et al., 2011), or extension to include the wider range of impacts that might be associated with the use of varying fishing gears (including, for example, emissions associated with fishing fleets)"). In our study we haven't conducted assessments of the exploitation level of individual stocks (reviewer example c.) but we do mention the potential to do so in future studies in our Discussion.*

In summary, we feel that the abstract does already indicate the need to look beyond the 'aggregate' within these assessments. Furthermore, we feel there is potential to use CBAs for fisheries to address the perspectives included in the examples provided by the reviewer, either with the current data that we have provided (e.g. via the full datasets that we include in the Appendices) or that could be provided with further advances. It is beyond the scope of the article - and the word limits imposed - to provide an exhaustive assessment across these varied aspects that comprise a holistic understanding of the sustainability of fisheries. Therefore within the Discussion at the moment we have (as identified by the reviewer) done our best to draw attention to opportunities for improvement and further analysis.

P4L15-19 repetition, I suggest removing the sentence starting with Yet…

RESPONSE

We have removed the sentence "Yet, the number of studies incorporating species removal or other environmental pressures are few, with most studies reviewed only discussing fishery-specific pressures outside the LCA methodology and in qualitative terms (Avadí and Fréon, 2013)" as suggested.

P4L56-61 Inconsistent. As I've read this, you criticise CREEA on the previous page (P3L29-39) for doing this type of rough (discard) assessment, but here you state another source/method doing another simple and ecologically irrelevant discard index. Do you approve of the Global Discard Index as a robust method, but not CREEA? And if so, why choosing the GDI approach?

RESPONSE

The criticism of the CREEA method on page 3 is actually intended to be more specifically focused on the overall aggregation of data rather than the methods employed for discard *assessment (although as highlighted in our Methods, these are also flawed). We have removed part of the sentence on page 3 to remove reference to discards from this section so that this now reads: "Instead, marine and inland catches were aggregated to provide a value, in tonnes, representing total biomass extraction (Merciai et al., 2014)".*

On page 4, we draw attention to the Global Discard Index as an example of the consideration given to discards within LCA-focused studies. This example was added in response to the previous set of reviews. Within the text on page 4 we do not feel we 'endorse' this method and it should be noted that it is not the Global Discard Index that we later adopt in our study (rather a modification to the CREEA method as described in Section 2.2). It should also be noted that the discard estimates we adopt are a clear improvement on the basic assumptions used for 'unused extraction' within typical material footprint accounts (which are the basis for the CBA developed here) yet are broadly consistent with these previous approaches. We are clear within our Discussion that advancements to discard estimates are warranted in future CBA development for fisheries e.g. "The discard estimates utilised here - whilst offering improvements on previous best practice within consumption-based accounting - do not reflect the full diversity of discard rates that will occur across different fisheries and species groups in practice. Nor do they measure of any captured fisheries production (i.e. that reported in the FAO FishStat database) that is wasted after landing that would ideally also be classified as an 'unused' component of the fisheries economy. There are a number of datasets that provide opportunities to improve upon the integration of fisheries-linked information that a disaggregated CBA for fisheries would allow.".

P5L25-54 this reads more like belonging to methods section

RESPONSE
We agree with the reviewer. We have removed these lines from the Introduction and integrated some of the content into the Methods (Section 2.1) which provides the overview of data sources.

P6L4 discuss caveats of using discard rates for three species-linked groups based on literature. Maybe relate to:
*Zeller, D., Cashion, T., Palomares, M., & Pauly, D. (2018). Global marine fisheries discards: a synthesis of reconstructed data. Fish and Fisheries, 19(1), 30-39.

RESPONSE
As stated above, in the Discussion we already highlight that our discard rates do not reflect the 'diversity' of reality. We have also already referred to the Sea Around Us dataset in the Discussion, but we thank the reviewer for pointing out this improved reference which we have integrated: "Repositories of information such as Sea Around Us (Pauly and Zeller, 2015; Cashion et al. 2018; Zeller et al. 2018) have compiled estimates of capture methods and discard quantities across different species and regions/countries of capture. Whilst exploration of these datasets suggests they will not comprehensively cover all species and locations of capture covered by FishStat statistics, in combination with the FishBase repository they could be used to improve the integration of capture and discard information into consumption based accounts in future" .

P6L29 several seafood LCAs has shown the importance of stock status rather than capture location. Why is capture location seen as relevant here but not stock status?

RESPONSE

Capture location is included as a key part of the data missing from pre-existing consumption-based accounts and one that is readily available within FAOStat. We do not regard stock status to be irrelevant (far from it), but integration of stock status information would be a much more resource intensive activity (the trade-off between resource intensity and improvements to data is something we refer to in the Discussion: "Such advances must be weighed against the additional complexity and data-intensity that such improvements would entail, and therefore - as for all environmental assessments of this type - methods should be carefully designed with regard for the granularity of information that is sufficient to highlight, and respond to, consumption-driven pressures.").

Stock status integration is something we encourage for future studies in the Discussion: "Even where this data is present, the species-level information utilised from FishBase in this paper is typically only comprehensively available for a 'general' global stock, and does not vary temporally or spatially. However, the catch method or vulnerability of individual stocks is also important in fisheries management; one stock can potentially be depleted whilst others remain sustainably managed, and species can be harvested from the same, or different, regions of the sea using more or less damaging methods" and "There are a number of datasets that provide opportunities to improve upon the integration of fisheries-linked information that a disaggregated CBA for fisheries would allow. The International Council for the Exploration of the Sea (ICES), for example, provides detailed stock assessments which could be linked to the regionally specific capture information provided in FAO. Indeed, spawning stock biomass information based on this repository has been assessed as providing a robust indicator for consumption-activity (Eisenmenger et al., 2016) in the form of 'Fish catch outside safe biological limits', which was compiled by EUROSTAT for reference years 1994 to 2010 (EU, 2012), but has recently been discontinued (pers. communication). A major limitation of the ICES stock assessments is that they are geographically limited to Northern Atlantic regions, which restricts their applicability in global assessments. However, the integration of similar regional stock assessments (for example, information in repositories such as RAM Legacy; Ricard et al., 2012) into consumption-based accounts is likely an avenue for further research.".

Of course, any integration of stock status information within CBAs relies on the identification of the source of this production (which can then be associated with geographically-defined stocks) and therefore the inclusion of locational information in this study is a pre-cursor to more advanced analysis.

P6L58-59 discuss relevance/caveats of aggregating fished and farmed seafood from a footprint perspective

RESPONSE

We discuss this limitation in the Discussion: "Furthermore, EXIOBASE does not distinguish between the economic activity of capture fisheries and aquaculture, so average demand-side relationships are used. Whilst this issue is not unique to fisheries, and indeed is a problem to some degree with any MRIO-based consumption account (c.f. Lenzen et al.

2012), whose method of allocating species extinction threats to global consumption faces similar issues), for the presented results it does limit the ability to place certainty on the inter-country trades of specific species. Recent data and methodological advances in this field could help significantly in overcoming these issues. For example, in addition to the production information present within FishStat, trade data from FAO and UN Comtrade contain species-level information on the trade of fisheries products that might be utilised to allow more specific trade information to be integrated into consumption-based accounts"

P7L14-19 I would like to see a table with input data and source to the model (e.g. feed, …) to better understand what you've done and limitations

RESPONSE

We understand the need for transparency in the underlying inputs to the EXIOBASE model but feel that adding a table to this manuscript is unnecessary as the EXIOBASE model and its formulation is extensively documented in Stadler et al. 2018 (referenced within our paper). We have, however, moved this reference forwards in the text so that it links more closely to the section where we describe the model.

P7L39-45 for consumption-based accounts, edible yield (varies a lot between species) and use of landings (feed or food) is highly relevant. Why use live-weight?

RESPONSE

Live-weight is the unit of measurement provided by the FAOStat database which is attached to the EXIOBASE model as an 'extension' to the consumption-based account. The 'footprint' as measured here is thus in units of live weight. The economic 'use' of this live weight is estimated via the distribution from source-to-sink/production-to-consumption that the MRIO model EXIOBASE allows. Inherent in this distribution will be the alternative uses of the 'live weight' of the fisheries product across the entire global economy for both food, feed and other uses (we describe this in the Discussion: "our methods include consumption of fish products embedded in the full suite of consumption activities (which includes use not just directly for food, but also fish production embedded in feed products used in livestock and aquaculture industries, industrial products, and other goods and services)"). As described in the Discussion (and see response above) a dependence on EXIOBASE to conduct this distribution is not without its limitations but is consistent with usual material-footprinting/consumption-based accounting practice. In short, the use of live weight is not mutually exclusive to the importance of the use of the product… quite the opposite.

As highlighted in a later reviewer comment, since we undertook this study an additional study which contains a single-year fisheries-specific MRIO has been undertaken which offers some advantages in terms of the treatment of feed/food for the fisheries product. However, it also has some disadvantages which are described below in response to the reviewer's referral to this new paper.

P7 2.1.3 motivate better why you've chosen the attributes you have (given the importance of fishing pressure and stock status).

RESPONSE

These attributes are simply those available in FishBase and we believe we are clear in the Methods (previously Introduction) that these are not exhaustive ("Whilst we have utilised FishBase as an exemplar for this study, it is clear from the review of LCA applications above that information allowing for a more complete understanding of the pressures imposed by fisheries consumption is becoming increasingly available, with datasets likely to continue to improve in future.") and that there are opportunities for inclusion of more detailed analysis ("The limitations associated with the use of FishBase, FishStat and EXIOBASE are therefore elaborated in the Discussion along with broader coverage of improvements that should be targeted for the fisheries accounts presented in this study to increase their rigour and policy relevance").

P8L15-18 yes the forest clearcutting reference is highly cited, but nuances have been snowballing since. I suggest a more nuanced approach to present this also here to- the fishing effort is highly aggregated (check e.g. https://www.benthis.eu/en/benthis.htm).

RESPONSE
We accept that the picture is more nuanced than this well-cited example might suggest. Therefore, we have modified the sentence with the addition of a new reference from the suggested resource to read: "trawling causes physical disruption to the seabed and has even been compared to forest clear-cutting due to its impact on benthic communities (Watling and Norse, 1998; Depestele et al. 2016)."

Methods (in general): why haven't you included greenhouse gas emissions?

RESPONSE
Greenhouse gas emissions are already embedded within dedicated consumption based accounts for GHGs that are covered in other studies and therefore it was beyond the scope of the article to look at this area. We agree with the reviewer that there is scope for the investigation of GHGs of fisheries in more detail within CBA (something that is mentioned in the Discussion). See also response to point 2 above.

P9L33-59 are you incorporating the Global Discard Index mentioned before you mean? I this case, I think you should also report on limitation to using this, even if it may represent an improvement to existing methods. There is also a FAO report by Petri Suuronen on discard survival rates.

RESPONSE
No - we don't use the Global Discard Index developed by Vázquez-Rowe et al. but we do use Kelleher 2005 data which is also used in the compilation of the GDI. The root of our work is material footprinting and we have improved upon the approach developed in CREEA. We have adjusted the text in the methods to try to make it clearer that we are adopting the discard coefficient equation utilised by the CREEA project, but that we improve upon this by revising discard rates: "An 'unused extraction' or 'discard' coefficient, as adopted in the CREEA study, is calculated.." and "In this study, to address flaws in the previous estimates, we use updated discard rates, d."

The limitations of this approach are elaborated in the Discussion and we acknowledge that more work to integrate species and gear-specific survival rates could also be integrated. We *have therefore modified slightly a sentence in the Discussion to clarify this, including the reference highlighted: "Whilst exploration of these datasets suggests they will not comprehensively cover all species and locations of capture covered by FishStat statistics, in combination with the FishBase repository they could be used to improve the integration of capture and discard (and associated survival; Suuronen 2005) information into consumption based accounts in future"*

P10 on Data integration- how have you included farmed species? Unclear how you treated this sector. I see no information on feed input or feed conversion ratios? Aquaculture has developed a lot over time, and so has feed composition, but a considerable part of the live-weight fish in your consumption model is actually input to the farmed seafood components in the form of feed (either based on whole fish or processing byproducts).

RESPONSE

Aquaculture species as a separate 'product' are included in the FAOStat production dataset that is used as an extension to the EXIOBASE model. There is thus a separate material 'footprint' for aquacultural production.

However, the reviewer refers primarily to the use of capture fisheries products as a feed for aquacultural production. Our model allows for this: Products of capture fisheries that are used in the aquaculture industry will be accounted for in the economic redistribution that the the EXIOBASE model conducts (see response above and the slightly adjusted sentences: "EXIOBASE is a global MRIO model, with domestic production and consumption linked via bilateral trade data between sectors and economies to capture the interrelationships across international supply-chains from where an extractive industry takes place (e.g. capture of wild fish), through to processing/manufacturing and trade to final demand for the goods and services" and "MRIO databases inherently capture the embedded nature of extraction, processing, trade and consumption within and across the regions along a supply chain"

The use of fish in feed (for aquaculture or other animals) is embedded in the 'processing' stages which EXIOBASE captures. Therefore, our model does capture the use of fish in aquaculture (and all other industries).

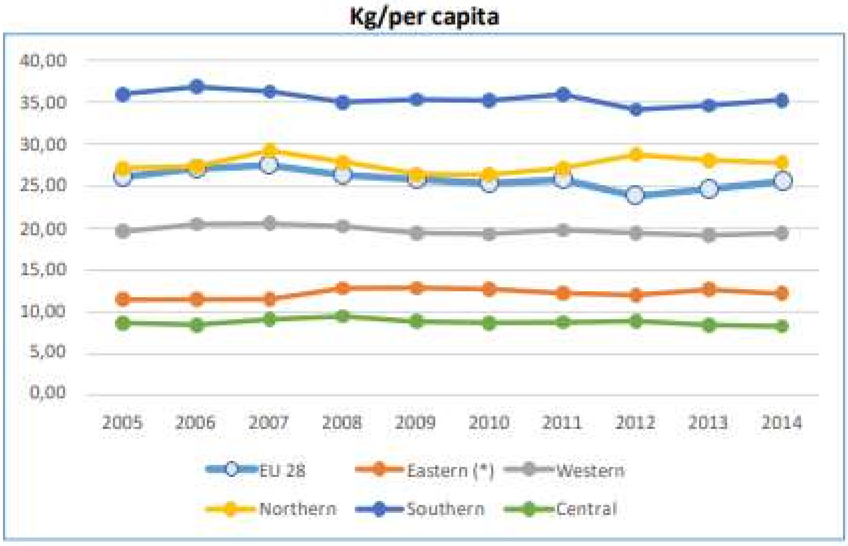
We acknowledge certain limitations of EXIOBASE in the Discussion "aggregating all fisheries products into a single sector means that trade linkages within the model treat all products homogeneously, disguising the fact that specific products will have different supply chains. Furthermore, EXIOBASE does not distinguish between the economic activity of capture fisheries and aquaculture, so average demand-side relationships are used" and suggest future improvements.

In response to a previous comment we have made the underpinning reference for the EXIOBASE model more explicit in the text which is the source of further information about how the MRIO distributes any given product through the economy.

P11L19 how come Europe has a negative trend in seafood consumption- according to EU fact sheets it is rising? Is this per capita, then this is the results of demography I guess. Please explain/clarify. And compare your consumption of 23.4 kg LW with the most recent FAO estimate (report in 2018) of 20.3 kg. Why are your figures different?

RESPONSE

This is an extract from an EU fisheries report (http://www.eumofa.eu/documents/20178/84590/EU+consumer+habits_final+report+.pdf) on fish production consumption which indicates that consumption fell between 2005 and 2012 before recovering slightly in 2013 and 2014.



Our own results also indicate a fall over the timeseries but no upturn in 2013 and 2014. Per capita results for 'Europe' from our study (available in an Appendix to the manuscript) indicate a fall from ~29.9kg per person in 2005 to 25.2kg per person in 2014. This compares with the average of 25.8kg over this time-series quoted by the EU report.

The discrepancies between data are not unexpected for two reasons. Firstly, composition methods differ. As highlighted in the Discussion where we make comparisons to FAO data, our results are an estimate of the TOTAL consumption footprint of fisheries (i.e. direct and embedded consumption across all sectors) and not simply food consumption: "FAO estimates that supply of fish products for human food consumption reached around 20kg per capita in 2014 (FAO 2016a). Due to the fact that our methods include consumption of fish products embedded in the full suite of consumption activities (which includes use not just directly for food, but also fish production embedded in feed products used in livestock and aquaculture industries, industrial products, and other goods and services), results from our CBA indicate that consumption activities are linked to 13.1 kg of (used) fisheries production per capita in 2014, plus a further 10.3 kg per capita from aquaculture, bringing total used consumption to 23.4 kg per capita."

Secondly, the 'Europe' classification used to summarise our results in the manuscript includes not just the EU-28 but also estimates for other countries on the European continent, including Russia.

Conducting an exhaustive comparisons across the various reports and methodologies that estimate trends in fisheries consumption and/or trade would require an intensive meta-analysis and cross-comparison of underlying methodologies that - whilst no doubt interesting - are some way beyond the scope of this work. Please see other responses below for further elaboration of this point.

P13L4-41 would benefit from validation/comparison with e.g.
*Watson, R. A., Green, B. S., Tracey, S. R., Farmery, A., & Pitcher, T. J. (2016). Provenance of global seafood. Fish and Fisheries, 17(3), 585-595.
*Swartz, W., Sumaila, U. R., Watson, R., & Pauly, D. (2010). Sourcing seafood for the three major markets: The EU, Japan and the USA. Marine Policy, 34(6), 1366-1373.

RESPONSE
In our existing manuscript we have already made reference at a high level to the results of Watson et al. 2016 but have now also integrated a reference and high-level comparison to the work of Swartz et al (2010): "As illustrated by Watson et al. (2016) in analysis of trade in fisheries products, fish products are increasingly traded and have been subject to an expansion of trade routes over time. Developing countries are often net exporters of fish products, with developed countries net importers (Swartz et al., 2010). Similar results are indicated in our CBA analysis, with many developing regions of the world acting as net exporters (Figure 2) and diversification in sourcing regions for consumption apparent throughout the timeseries (Figure 3). "

We feel that going beyond a relatively high-level comparison to these datasets is beyond the scope of our manuscript, due to the very different methodologies employed. For example, Swartz et al. (2010) essentially undertake a process of algorithmic matching between consumption of capture fisheries for food and fishmeal, trade statistics and production data. They state: "Both food and industrial (i.e., fishmeal) consumptions are evaluated, although the analysis, which excludes trades of aquaculture product, considers industrial consumers of fishmeal as the final consumer and thus does not take into account the indirect consumption of fishmeal by the consumers of aquaculture products (e.g., farmed salmons and shrimps)". This is is contrast to our CBA which does estimate all of these direct and indirect flows. The approach of Swartz et al could be useful in enhancing full CBA accounts in future (and we have added a reference to the manuscript towards the end of the Discussion where we talk about such enhancements) and moving towards a state where approaches become more harmonised.

However, in order to conduct a comparison at any level of detail between our own results and the results of other papers that have looked at fisheries trade, an elaboration/meta-analysis of the assumptions and methods underpinning each approach would be warranted with comparisons made across scales, geographies and species compositions. Such a comparison is significantly outside of the scope of our own paper and we feel it is inappropriate to draw too much comparison (except that at a high level - which we have included) until such time as a more exhaustive analysis can be conducted.

We present a further example of the difficulties of comparing datasets in a response below.

In terms of the lessons for the 'validation' of our study we would highlight two aspects a) that the approach of distributing the material consumption of fisheries products adopted is fully compatible with established material footprinting methods and b) (and as a result) in contrast to other studies it ensures that overall consumption is equivalent to production and therefore ensures that the fisheries trade and processing system is holistically represented.

P14 Figure 2 I was surprised to not find Peru here? Anchoveta is one of the key stocks in the world. It would also be good to validate/compare your results on gears with:
*Cashion, T., Al-Abdulrazzak, D., Belhabib, D., Derrick, B., Divovich, E., Moutopoulos, D. K., ... & Pauly, D. (2018). Reconstructing global marine fishing gear use: Catches and landed values by gear type and sector. Fisheries Research, 206, 57-64.

RESPONSE
Whilst it covers the entire global economy, the EXIOBASE model does not provide country-level detail for all world regions. Peru, for example, is aggregated into a 'Rest of World America' region. When 'extensions' are added to the model these must be allocated to the appropriate region of the model so captures from Peru (and other countries in the region) are allocated to the 'RoW America' region of EXIOBASE. Figure 2 indicates the importance of the RoW America region as a key net producer/exporter which therefore aligns with the reviewer's comment.

Thank you for drawing our attention to the Cashion et al. (2018) paper which is linked to the Zeller et al. paper mentioned earlier. By comparison, our own data on catch methods is crude as it is linked only to species as a 'main catch method'. This is a fact that we openly acknowledge in the manuscript. We have, however, now also cited this paper in the Discussion where we talk about the potential to improve upon our gear estimates: "Repositories of information such as Sea Around Us (Pauly and Zeller, 2015; Cashion et al. 2018; Zeller et al. 2018) have compiled estimates of capture methods and discard quantities across different species and regions/countries of capture. Whilst exploration of these datasets suggests they will not comprehensively cover all species and locations of capture covered by FishStat statistics, in combination with the FishBase repository they could be used to improve the integration of capture and discard information into consumption based accounts in future". We feel a comparison of our own data to this data would be valid if the improved catch method data was presented from the perspective of consumption (which it is not currently) and even then this would only be appropriate in the context of the meta-analysis/full elaboration of methods mentioned above.

P16 Figure 4 maybe I've missed something, but I feel the need for explanation/motivation on why estimating and including discard here?

RESPONSE
We have estimated and included discards throughout the results presented in the paper. Figrue 4 is included to a) draw attention to the most 'discard heavy' group of species and b) to offer an alternative perspective that a CBA allows that isn't apparent from previous figures i.e. that of the 'distribution' of species to different markets (which may vary as illustrated by the producing region's context).

Discussion (first paragraph): relate your results to the papers I've earlier mentioned (Watson, Swartz). Maybe this perspective has not been within a specific field, but that said, it is not as if it has not been studied by others, e.g.
*Guillen, J., Natale, F., Carvalho, N., Casey, J., Hofherr, J., Druon, J. N., ... & Martinsohn, J. T. (2018). Global seafood consumption footprint. Ambio, 1-12.

RESPONSE

We thank the reviewer for drawing our attention to this additional paper (Guillen et al. 2018) which has related objectives and methods (but some key differences) to our own.

The Guillen et al. paper creates a seafood-specific MRIO to create a 'seafood consumption footprint'. The MRIO presented by Guillen et al. can be thought of as a 'partial' MRIO as it does not holistically capture all economic sectors or consumption activities in a global economy. This is in (subtle but methodologically and analytically important) contrast to our own paper which extends an existing economy-wide MRIO with fisheries-specific details. The paper claims (which we don't dispute) to reconstruct for the first time the global fisheries biomass flows in national supply chains to estimate consumption footprints at the global, country and sector levels. Our paper has a similar, but distinct, claim to "present, for the first time, a dedicated consumption based time-series for capture fisheries, disaggregated to the level where insights can be provided into the pressures imposed on the fisheries system, and the localities in which these pressures occur".

The key differences between the approaches are as follows:

- *Guillen et al 2018 create an MRIO from detailed fisheries-specific data in physical units (mass) vs. we use a pre-existing economic MRIO with attached physical production information.*
- *Guillen et al 2018 create an MRIO which is not 'economy-wide' but instead focuses on fisheries trades and processing for food use (they effectively use four 'sectors' to represent the fisheries economy: aquaculture, fisheries, fish processing and marketing, and fishmeal reduction, which do not exhaustively represent economic sectors to which fisheries link) vs. our approach which adopts a pre-existing MRIO that accounts for ALL economic transactions. The former will almost certainly account for processing activities with greater accuracy than our own approach but at the expense of a time-series (see below) and at the expense of providing a holistic overview of the fisheries footprint associated with ALL consumption activities (compared to food consumption only) which our method provides. (As the author's highlight in their paper "In 2014, around three quarters of the global fish production not destined for direct human consumption was reduced to fishmeal and oil" but their method does not allow for the distribution of the remaining quarter of non-food use whereas ours does).*
- *Guillen et al 2018 frame final 'consumption' activities into two categories of demand: human consumption and consumption by the fishmeal and fish oil industry. In a traditional economy-wide consumption based account the second would actually be an intermediate category of consumption (which outputs from this industry being consumed by humans in meat products, for example) vs our method which adopts true 'final demand' activities across all sectors of the economy as drivers for fisheries production and therefore offers a more 'traditional' consumption based footprint.*
- *Guillen et al 2018 present their results in terms of mass vs our results extend analyses further by incorporation of fishing area location, capture method and life-history data.*
- *Guillen et al 2018 do not incorporate an unused extraction component vs our method attempts to calculate an unused extraction component (discards).*
- *Guillen et al 2018 present data only for a single year vs our method presents a time-series.*

The last point is particularly pertinent. In order to monitor changes over time (as illustrated in our paper) time-series must be compiled. Traditionally, time-series preparation within MRIO research has been a data-intensive process which likely explains why the Guillen et al 2018 study only provides a single year: the process of "reconstructing inter-industry flows of seafood biomass between countries, reconciling discrepancies in FAO and COMTRADE official statistics and reconciling published technical coefficients on feed use and seafood inputs for fishmeal and fish oil production" is far from trivial and very resource intensive. However, there are certainly important advances contained within the Guillen et al 2018 paper which are important for our own paper to acknowledge and indeed complement our call for the integration of more detailed material flow/mass based data into consumption based models. We have therefore added a reference and short description of the scope of this paper both to the Introduction and to the Discussion:

- *In the Introduction: "Guillen et al. (2018) present a recent example of a CBA that exclusively covers sectors relating to fisheries and their products. In doing so, they integrate a detailed material-based account of the key sectors involved in fish production and processing, but do so for a single year only, and at the expense of presenting a comprehensive account of all the economic and consumption activity to which fisheries are linked."*
- *In the Discussion: "Such approaches have successfully been adopted in consumption-based accounts for terrestrial products (see, for example, Ewing et al., 2012; Stadler et al., 2018) and for fisheries within the context of a CBA which offers partial coverage of global economies (Guillen et al. 2018). Recent methodological advances, and increased data availability, have also demonstrated the potential to link sub-national trade information to global supply chain modelling (Godar et al., 2015; Croft et al., 2018)."*

Whilst both manuscripts rely on an MRIO, the different methodologies mean that a direct comparison of results - as mentioned above in our response to other comments - is difficult due to the different unpinning methods which will alter results, and also due to the very different regional classifications adopted.

For example, the global per capita consumption footprint in 2011 is estimated by Guillen et al 2018 at 27kg in 2011 which is higher than our equivalent result of 22.4 kg in 2011. The Guillen et al 2018 estimate appears somewhat high to us because - according to FAO Statistics - production in capture fisheries was 93.6 million tonnes in 2011 and aquaculture production 61.9 million tonnes. Assuming a global population of 6.93 billion in 2011 (as used in our analysis based on data obtained from the World Bank in Jan 2018) results in an estimate of per capita <u>production</u> across capture and aquacultural sources of 22.4 kg per person. In our model, global consumption equals global production so our estimate of consumption per person matches the per capita estimate of production. We suspect the answer lies in the way in which their model was constructed (which depends on balancing of data via a rake-and-scale (RAS) method, in this case specifically to scale <u>up</u> country-level production to meet reported demand). As they state, "fisheries official statistics suffer from data quality and missing data issues and consequently the overall production, trade and consumption levels did not match". The authors have chosen to balance to the consumption-end of the data, however this is not the only option to reconcile the discrepancies. This illustrates the complexity of making comparisons of this type, and we believe supports our *position that undertaking comparisons across estimates derived from different modelling approaches and datasets warrants more extensive investigation which is beyond the scope of our paper.*

P17L12- Well, with increasing effort and catches plateaued this strongly affect LCAs, which are strongly affected by catch per unit effort, and has shown that the footprint has increased in some fisheries over time from e.g. poor stock status, change in target species/gears. See e.g. recent estimates on global GHG-emissions and one on a more local perspective (Swedish):
*Parker, R. W., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., & Watson, R. A. (2018). Fuel use and greenhouse gas emissions of world fisheries. Nature Climate Change, 8(4), 333.
*Ziegler, F., & Hornborg, S. (2014). Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002-2010. Marine Policy, 44, 72-81.

RESPONSE
As the reviewer suggests, the fact that catches have plateaued but effort is increasing would indeed result in greater GHGs from fishing fleets. However, as per our response above, the GHG emissions perspective is not within the scope of this paper. As stated, at this point in the paper we refer to the perspective offered from a 'material footprint' viewpoint that would given an inaccurate impression of the relative importance of sustainability considerations compared to other types of material consumption. We go on to say: "However, this material consumption perspective, whilst valid when assessing holistic material resource efficiencies associated with consumption, risks missing the rather more nuanced context of pressures that are associated with many products, including those of fisheries. As dependence on products of aquaculture increases, methods which allow disaggregated connections to be made between consumption activities and their sources and associated pressures are arguably even more relevant to ensure that continuing changes in consumption patterns and the nature of their links to individual ecosystems are not hidden to consumers via 'dilution' effects". This is in full agreement with the reviewer that the real 'footprint' may be increasing; our argument is precisely that a more nuanced perspective (in contrast to the one that material footprints alone offer) is needed to more accurately assess this.

P17L27 there is a new FAO report from 2018 with updated data

RESPONSE
The content of FAO Report from 2016 is actually more relevant to comparison with our study as the latest year in our data is 2014 - a timestamp that is explicitly referred to with the 2016 report. In the 2018 report, the years 2015 and 2016 are more commonly referred to, and therefore to aide the reader in obtaining the most accessible background information we have therefore retained the original reference for the high-level comparisons conducted in our paper.

P17L27-45 Maybe you need to clarify this I methods, but I'm not fully sure at his point how your estimate is embedded. Have you e.g. used byproduct streams from fish for human consumption as fishmeal input to pigs and aquaculture? Relate your results to:
*Guillen, J., Natale, F., Carvalho, N., Casey, J., Hofherr, J., Druon, J. N., ... & Martinsohn, J. T. (2018). Global seafood consumption footprint. Ambio, 1-12.

RESPONSE

This comment is linked to those above about the workings of the EXIOBASE model. We have existing text in the Methods that we believe describes the fundamental ability of MRIOs to capture ‘embedded’ production, but have made this more explicit with the inclusion of the word ‘embedded’ in the revised text e.g.: “MRIO databases inherently capture the embedded nature of extraction, processing, trade and consumption within and across the regions along a supply chain.”

Our response to the second part of this comment is also contained within our comments above.

*Title Page

Improving consumption based accounting for global capture fisheries

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Improving consumption based accounting for global capture fisheries

Highlights

1. A dedicated consumption-based time series for the impacts of capture fisheries.
2. Provides sustainability information and perspectives missing in previous accounts.
3. Fisheries discard estimates are improved.
4. Results show important shifts in catch composition within historical consumption.
5. Recent model and data advances offer opportunities for improved future accounting.

ABSTRACT

Consumption-based accounting has been used to understand the resource and environmental pressures associated with the consumption of goods and services. Capture fisheries have significant economic, cultural, and environmental importance, yet relatively limited attention has been given to understanding their consumption-linked pressures. Where products of marine and inland fisheries are accounted for, they are typically done so within the context of 'material' footprints or within life cycle assessment-based studies which draw more attention to resource efficiency or pollution-related aspects of fisheries than the species or ecosystem-linked consequences of the extraction process itself. However, the sustainability of fisheries products is highly dependent on the catch method, location, and species targeted. To date, these have been missing from consumption-based accounts. Here, a collation of species-specific information comprising vulnerability and environmental pressure associated with capture is provided, which is then linked to a global multi-regional input-output model to - for the first time - create a dedicated consumption-based time-series for fisheries. Whilst the aggregate footprint of global capture fisheries has remained stable in recent decades, our results demonstrate that at national or regional scales different trends in consumption exist. Importantly, there have been significant shifts in the composition of catch within these consumption accounts, which have potential implications for the sustainability of underpinning supply chains. This paper draws attention to the fact that material efficiency perspectives are insufficient in the assessment of pressures on the marine environment driven by consumption of fisheries products, and – whilst challenges remain - there is a growing abundance of information and development of methods that could potentially be utilised to overcome gaps in the future.

Keywords: fish, supply chains, sustainability, MRIO, footprinting, environmental accounts

1. INTRODUCTION

Consumption-based accounts (CBA), which reallocate the environmental or social pressures that occur at points of production to the end consumers of products and services, have been used in a variety of contexts to raise awareness of the trade-mediated linkages between consumption activities and the consequences that arise in remote production systems and the environments on which they depend. CBA - and the associated development of environmental and social ‘extensions’ to these approaches - remains an active area of research, but is also increasingly finding utility in policy and practice. For example, implementations of the ‘material footprint’ are recommended in the Sustainable Development Goal indicator framework (UN 2015), accounts have been developed by the OECD (Wiebe and Yamano 2016), UK (Defra 2018) and Sweden (*ref needed to Special Issue that this paper will sit within*), and CBA finds application in popular consumer-facing tools such as carbon footprint calculators (Roelich et al., 2014; West, et al., 2016). Methodologically, the prevailing approach for CBA is multi-regional input-output (MRIO) modelling, which has been applied to explore an ever-increasing set of pressures, or ‘footprints’, including greenhouse gas emissions, water resources, land use and biodiversity loss (Galli et al., 2012; Hertwich and Peters, 2009; Lenzen et al., 2012; Lutter et al., 2016). MRIO models explicitly capture the role of onward processing at the sector and country (or aggregations of countries into regions) level where, for example, goods are imported into a country, processed, and exported again (increasingly common for China, for example). As such, MRIO methods holistically capture the pressures or impacts associated with demand, typically within national economies, for goods and services. Utilisation of material resources underpins this demand, and products can be consumed relatively directly (i.e. with limited or no processing), or highly ‘embedded’ (i.e. used as inputs in intermediate processing stages). Analyses of the consumption of physical natural resources, and associated methodological advances, have tended to focus on products of terrestrial environments such as agricultural production systems or - more broadly - on the development of more generic ‘material footprints’ (Wiedmann et al., 2015). The latter is suited to resource efficiency assessments which provide information on the degree of coupling between an economy or consumption-based activity and natural resources (e.g. EEA, 2014) but, as an aggregate measure, provides little detail on whether consumption of one resource is more or less sustainable than any given substitute.

In comparison with terrestrial production systems, marine resources have had limited attention within CBA. As highlighted by Crona et al. (2016), around 40% of seafood is traded internationally but only limited attention has been paid “to the link between individual fisheries, global trade and distant consumers”. Marine exploitation is significant, with well-documented episodes of overfishing (Allan et al., 2005; Jackson et al., 2001; Pauly et al., 1998; Sissenwine et al., 2014), and pressing concerns around other forms of resource extraction such as deep-sea mining (Mengerink et al., 2014). Capture fisheries are unusual in that even large-scale commercial operations, although vastly more efficient and technology-led, remain similar to their pre-historical roots and involve the direct exploitation of wild species at a scale unmatched in terrestrial environments (Sahrhage and Lundbeck, 1992). Whilst aquaculture production is increasing rapidly, and is on course to become the primary source of fish-based protein globally (FAO, 2016a; World Bank, 2013), capture fisheries remain important as a global industry and from social, economic, and nutritional perspectives in many regions of the world (Dyck and Sumaila, 2010; McClanahan et al., 2015; Thilsted et al., 2016; Urquhart et al., 2013).

Existing consumption-based assessments that include fisheries products are limited by the granularity of their analysis, which tend to heavily aggregate the underpinning species-specific catch data. They are also prone to overlooking the risks of environmental damage that fisheries pose and their significance as an exploiter of biological diversity. Consequently, they rarely look beyond resource efficiency perspectives and have a rather narrow treatment of the broader context of fisheries sustainability. For example, within an EU-FP7 project - CREEA - material extraction information was compiled (including products of fisheries) and connected to a multi-regional input-output model (EXIOBASE) (Merciai et al., 2014; Wood et al., 2014a). The capture information (in addition to aquaculture production data) required to do this was provided by the UN Food and Agriculture Organisation (FAO) FishStat database (hereafter 'FishStat'). Whilst FishStat contains information at species level - which is important in considering any pressures on species or environments that, for example, interact with fish life-history characteristics or stock capture methods - the data was not employed with such specificity. Instead, marine and inland catches were aggregated to provide a value, in tonnes, representing total biomass extraction (Merciai et al., 2014). Fisheries information is also included in the well-known 'Ecological Footprint' compiled by the Global Footprint Network (Borucke et al., 2013), with the area (in global hectare equivalents) of fishing grounds incorporated based on estimates of the annual primary production required (PPR) to sustain the harvested species (Pauly and Christensen, 1995). Whilst providing an estimate of the biocapacity necessary to sustain fisheries production (but see Hornborg et al 2013 who question the adequacy of the PPR method for assessing fisheries sustainability), this does not provide contextual information relevant to broader fisheries sustainability, such as the nature of stocks harvested, or detail of the harvesting techniques that impact physically on the marine environment. Economy-Wide Material Flow Accounts (EW-MFA) represent another example where products of fisheries are embedded in estimates of national material consumption (Eurostat, 2013; Fischer-Kowalski et al., 2011). However, in compilation and presentation, the data provided by EW-MFA accounts, and projects such as CREEA and the Ecological Footprint, tend to be amalgamated alongside other resource-types. Given the comparatively small tonnage involved, the contribution of fisheries to material consumption is at risk of being overlooked in such accounts. Guillen et al. (2018) present a recent example of a CBA that exclusively covers sectors relating to fisheries and their products. In doing so, they integrate a detailed material-based account of the key sectors involved in fish production and processing, but do so for a single year only, and at the expense of presenting a comprehensive account of all the economic and consumption activity to which fisheries are linked.

Process-life cycle assessment (p-LCA) contrasts with input-output/MRIO-derived CBAs (sometimes also known as IO-LCA) in that p-LCA applications tend to offer more specificity on the production, logistics and processing steps in the supply chain, but at the expense of the completeness of the system boundary (Islam et al. 2016). The pressures imposed by fisheries are explored in somewhat greater detail in more focused studies reviewing the development of extensions for p-LCA. For example, Avadí and Fréon (2013) cite sixteen studies which have attempted to incorporate fisheries perspectives into LCA-techniques. As Ziegler et al. (2016) point out, capture fisheries have their "own set of environmental challenges regarding sustainability, including exploitation levels of target and by-catch stocks and ecosystem impacts". The majority of LCA studies to date (including recent examples) focus on production efficiencies from the perspective of, for example, global warming or toxicity effects (Abdou et al., 2018; Avadí and Fréon, 2013; Farmery et al., 2015). Woods et al. (2016) review the potential for incorporation into LCA of several drivers of marine biodiversity loss, including those linked to fishing. These include the effects of stock over-exploitation, and the effects of trawling which causes seabed damage. For trawling, they highlight a number of regionally-specific studies (e.g. Foden et al., 2010; Nilsson and Ziegler, 2007), but point out that the requirement for spatial information on habitat and pressures means that their application has been largely restricted to European waters. For over-exploitation, they highlight the Langlois et al. (2014) study that provides a species-level metric based on the levels of exploitation compared to maximum sustainable yield (MSY), and an ecosystem-level approach which estimates the capacity of the harvested ecosystem to regenerate removed biomass. Emanuelsson et al. (2014) suggest the use of a 'lost potential yield' (LPY) indicator for LCA studies that presents an "anthropocentric resource-based perspective" which - whilst correlating with any environmental damage associated with extraction - is only comparable within stocks in terms of ecosystem damage (Woods et al. 2016). Furthermore, the LPY indicator is suitable only for "stocks for which the required input data are available, which in practice means only the most important commercial stocks" (Emanuelsson et al., 2014). Whilst these are most likely to be the target of focused LCA studies (which are typically biased in coverage in seafood LCAs towards developed countries and high-value species; Vázquez-Rowe et al., 2012a) they do not represent the full complement of species exploitation that a consumption-based (footprinting) approach requires. Vázquez-Rowe et al. (2012b) discuss the problem of discards, conceptualising a 'Global Discard Index' (GDI) aimed at standardizing discard estimates with LCA for world fisheries and applying this in a case study. In order to compute the GDI, discarded volumes, catch and landing rates are required for the fishery(ies) being studied, which are compared against a global discard estimate (Kelleher 2005). Finally, Woods et al. (2016) review opportunities for the development of indicators of the indirect effects of biomass removal, such as the development of a 'depletion index' based on the intrinsic vulnerability of species to fishing pressure, but state that data to address a wider set of such effects are not available as yet.

Incorporating the environmental pressures associated with fishing - which can vary dramatically depending on the species targeted, the stock location, and the capture method utilised - is important for a holistic assessment of the sustainability of marine or inland fisheries exploitation, and to encourage the identification and acknowledgement of these environmental 'externalities' that are otherwise masked (Crona et al. 2016). The relative lack of attention on these pressures in existing CBA studies reflects a clear gap in the literature. In response, this study aims to build upon current practice - via alignment to established material footprinting approaches - to present, for the first time, a dedicated consumption based time-series for capture fisheries, disaggregated to the level where insights can be provided into the pressures imposed on the fisheries system, and the localities in which these pressures occur. The purpose here is to demonstrate the use of simple and globally-accessible data to extend aggregated mass-based metrics in order to encompass a consideration of technological, regional or life-history characteristics that define discrete fisheries.

Our outputs illustrate that incorporating extensions in addition to captured-mass information provides novel insights into the effects of consumption on marine environments. Updated estimates are included for discards associated with these fisheries, with discard rates disaggregated across three species-linked groups to provide more realistic discard estimates than previously compiled in material accounts (i.e. CREEA; Merciai et al., 2014). Illustrative results are presented from the perspective of the global consumption of capture fisheries products, and for selected individual countries, indicating trends over the last 20 years in consumption and production dependencies, sourcing regions and capture methods, fish vulnerabilities, and linkages between consumers and high-discard fisheries.

2. METHODS

2.1. Overview of Data Sources

We combined three primary components to create a consumption-based account (CBA) for fisheries covering the period 1995-2014. These resources are: a multi-regional input-output (MRIO) model (EXIOBASE) which models the international supply chain pathways between points of production and final consumptive demand; a database (FishStat) containing details of capture fisheries production quantities (and associated details such as capture location), where this production data is allocated to the producing fisheries sector for the appropriate country or world region within the EXIOBASE; a database (FishBase; Froese and Pauly, 2017; http://www.fishbase.org/) containing species-specific information which are used to 'extend' the information provided by capture statistics. FishBase contains detailed information suited to developing an understanding of the broader consequences of fisheries consumption on species and the environment, via economy-wide consumption-based modelling. FishBase (and its non-finfish counterpart SeaLifeBase; Palomares and Pauly, 2017) - managed by a global consortium with regular contributions from the academic and fisheries management community - offers taxonomic, population distribution and dynamics, life-history and ecological information. Whilst we have utilised FishBase as an exemplar for this study, it is clear from the review of LCA applications above that information allowing for a more complete understanding of the pressures imposed by fisheries consumption is becoming increasingly available, with datasets likely to continue to improve in future. However, due to the relative nascence of the use of fisheries information in CBA, the current methodological and data landscape remains challenging. The limitations associated with the use of FishBase, FishStat and EXIOBASE are therefore elaborated in the Discussion along with broader coverage of improvements that should be targeted for the fisheries accounts presented in this study to increase their rigour and policy relevance.

Further details of the component datasets, and the derivation of fisheries discard rates for incorporation into the resulting CBA, are detailed below. Unless otherwise specified, all results presented in this paper are outputs from this CBA.

2.1.1. EXIOBASE

EXIOBASE is an MRIO model developed by a research consortium across a number of EU-funded projects, including EXIOPOL, CREEA and DESIRE. EXIOBASE has a detailed homogeneous product classification across countries, with the production of 200 product groups by 163 industries modelled for 44 countries plus five aggregated 'rest of world' regions ('RoW Africa', for example, is an aggregation of many different African nations). EXIOBASE is a global MRIO model, with domestic production and consumption linked via bilateral trade data between sectors and economies to capture the interrelationships across international supply-chains from where an extractive industry takes place (e.g. capture of wild fish), through to processing/manufacturing and trade to final demand for the goods and services. EXIOBASE has a specific sector for fisheries that includes both wild capture and aquaculture based on the NACE1.1 classification, "Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)". In turn, the economic input-output data for this sector is based directly on national input-output statistics for each country in the case of European countries and most major economies (Australia, Canada, US, Japan, South Africa, India, Indonesia etc), whilst a disaggregation of the sector based on FAOSTAT data from an overarching agriculture, forestry and fisheries sector was done for regions such as China and Russia (Wood et al. 2014b). EXIOBASE provides supply and use tables, and where - for example - other industries such as food processing engage in fishing activity, a supply of fishing activity by the food processing industry is shown in the supply table. Conversion to square input-output tables follows the industry technology assumption (Majeau-Bettez et al. 2014). The phenomenon of 're-exports' (direct export of imported products with no consumption or further processing, which can result in a misattribution of product source) is not of concern as trade within the model is estimated between the originally exporting company and final importing country, whilst MRIO databases inherently capture the embedded nature of extraction, processing, trade and consumption within and across the regions along a supply chain (see Stadler et al. 2018 for more information). EXIOBASE version 3 (available online to 2011 at exiobase.eu, with later data available on request) includes an estimation of MRIO tables from 1995 to 2016 (more recent years had relatively less data to inform the estimates, and a form of "now-casting" was performed to update based on estimates of structural change, trade data and macro-economic data; Stadler et al. 2018). For the purposes here, data to 2014 is used, which includes detailed product level bilateral trade data.

2.1.2. FAO FishStat

The most comprehensive source of global production data for marine and aquatic capture fisheries and aquaculture production data is the FAO FishStat database (FAO, 2016b; Garibaldi, 2012), which contains information on production at country level from 1950. Catches are attributed to the country of the flag flown by the fishing vessel, which is also the country responsible for the provision of this data to FAO (DANIDA, 1999) (see also Discussion). Catches are expressed in live weight, i.e. the nominal weight of the organisms at the time of capture, with data presented at species level where available and with new data uploaded each year. Details of the broad capture location are generally included for capture fisheries (divided into FAO Fishing Areas, for inland and marine catches) which this paper utilises in the fisheries account as an 'extension' to the results.

2.1.3. FishBase

The presence of species-level capture information within FishStat makes it possible to link additional information associated with pressures on the environment and species as 'stressors' for use in consumption-based assessments.

FishBase (Froese and Pauly, 2017) is a global species database of finfish. Importantly, it includes details of species characteristics, with the following two attributes utilised in this analysis. (Other data are also available, which are described and available as extensions in the Appendix, but are not analysed.):

- Main catch method: details the typical method used to catch the species, aggregated across all fisheries. Ten primary methods are listed: trawling, seine netting, hooks and lines, traps, gillnets, castnets, 'various' gears, scuba diving, skin diving, and 'other'. Of these, seine netting and trawling dominate; global fish catch in 2014 included 27,903 kt of fish typically caught by seines, and 13,316 kt caught by trawls (including both used and unused fractions; see Section 2.2). A further 57,407 kt of fish were not classified with a main catch method. From an environmental impact perspective, seine nets have been associated with problems such as the bycatch of marine mammal species (Bellido et al., 2011), whereas trawling causes physical disruption to the seabed and has even been compared to forest clear-cutting due to its impact on benthic communities (Watling and Norse, 1998; Depestele et al. 2016). Within FishBase, some additional information on the capture method is present (such as, for example, the general use of 'bottom otter trawls' for Atlantic cod, *Gadus morhua*), and is integrated into the environmental extensions where available.

- Vulnerability score (0-100): the vulnerability metric is based upon a study by Cheung et al. (2005) that estimates the intrinsic susceptibility of a species to fishing pressure. This method uses readily-obtainable life history and ecological characteristics (maximum length, age at maturity and maximum age, natural mortality, geographic range, fecundity and spatial behaviour) and a heuristic "fuzzy expert" system to infer vulnerability. Vulnerability scores are not adjusted based on exposure to fishing effort across stocks. This method provides a good proxy in the absence of in-depth extinction vulnerability assessments that would conventionally rely on information typically unattainable for marine fish species.

These scores are tied to the fish species within the FishBase repository, and are independent of temporal or spatial dimensions; within the CBA presented, changes in the compositions of these attributes within consumption profiles are a result of shifting consumption patterns, rather than changes in the way species are assigned across extensions.

2.2. Discard Estimates

FishStat contains all quantities landed but excludes discards; fish which are caught but then thrown back into the sea. Reasons for discarding catch include, but are not limited to: captures are below size (and therefore outside limits imposed by management regimes, or unmarketable); fish are the wrong species, inedible or prohibited; there is not enough storage space on board; quotas are reached (Clucas, 1997). The reasons differ across fisheries and across the species groups. For example, high discard rate in shrimp fisheries result from relatively indiscriminate capture techniques. Previous work (CREEA project; Merciai et al., 2014) has estimated discards associated with fisheries catch, which can be considered a separate 'unused' output obtained from the environment (Eurostat 2013; Vázquez-Rowe et al. 2012b). An 'unused extraction' or 'discard' coefficient, as adopted in the CREEA study, is calculated as:

$$discard\ coefficient\ = \frac{md}{1-d},$$

where m is the mortality rate of discards, and d the discard rate.

The discard/unused extraction coefficient adopted in the CREEA project is based on calculations from Jölli and Giljum (2005), who estimate that for every 100 tonnes of marine fish caught, an average of 19.8 tonnes are discarded (d = 0.198). A single discard rate was assumed for all captured landings, with no attempt made to disaggregate data to different fishery types. Additionally, their estimate takes no account of the fact that the mass of total catch in each species group (present in the underlying FAO data on which their calculations are based; Alverson et al., 1994) requires the calculation of a weighted mean. When this is calculated from the original data, it results in a discard rate of 0.167 (author's calculation; not shown). Furthermore, an update to FAO's discard estimates provided in 2005 (Kelleher, 2005) estimates a weighted discard rate of 0.08 (using different methods compared to the 1994 study), concluding that the previous study's "estimates no longer constitute a true reflection of current global discard levels and continued citation of the paper's estimates as such is inappropriate".

In this study, to address flaws in the previous estimates, we use updated discard rates, d. Whilst the report by Kelleher (2005) does not contain a readily accessible, holistic species-group breakdown, it does provide rates for selected groups. For shrimp fisheries the statistics provide a weighted discard rate, d, of 0.623, and for tuna fisheries they provide a rate of 0.129. Deducting the mass of shrimp and tuna discards from the total returns, the discarded mass for 'other' species can be used with the remaining landed mass to deduce an associated discard rate of 0.055. Here, these updated rates for tuna, shrimp and 'other' fisheries are utilised in the data preparation. Accepting that mortality rates vary widely by species and fishing context, but in the absence of mortality information within the Kelleher (2005) study, this paper adopts the simple assumption of a discarded mortality rate, m, of 98% for all species, as per Jölli and Giljum (2005) and Merciai et al. (2014). Resulting coefficients are 1.619 for shrimp, 0.145 for tuna and 0.057 for 'other' species. These are assigned to FAO landings according to taxonomic order, with landings from the order Scombroidei corresponding to tuna, Natantia and Reptantia corresponding to shrimp, and all remaining orders being assigned the 'other' coefficient. In the absence of accessible datasets for inland fisheries, inland captures are assigned the same coefficients as marine captures.

2.3. Data Integration

A species list (covering all fisheries products in the database) was extracted from FishStat (FAO, 2016b). This list included 2,207 unique entries containing common names, latin names, and associated taxonomic family and order information. FishBase has an application programming interface (API) which is accessible via the R library 'rfishbase' (Boettiger et al., 2012; R Core Team, 2017).

An R script (which can be found as an Appendix) was written to loop through each species entry in the list with corresponding information extracted from FishBase via this API. This script first checks the species list to ensure that the data corresponds to an individual species and not an aggregated classification, and then checks for this species against the list within FishBase (or, for non-finfish species, SeaLifeBase). If a match cannot be made, the script uses the API's 'synonyms' functionality to check for alternative names for the species. 1,702 distinct species are resolved from the original list of 2,207 entries. Where a match is found, other information contained within FishBase is attached to the species record including the main catching method and the vulnerability score (plus also the trophic level, the resilience score, and the IUCN classification described in the Appendix but not analysed). Not all such information is present in the FishBase database for all species, with 1,317 having at least one type missing, resulting in these species being defined as 'unclassified' where data is not present. Only 20 of the resolved species are missing all information.

Landed catch (used extraction) and discard (unused extraction) quantities (alongside aquaculture production for comparison) are collated for each country or region of production, creating an 'environmental extension' sheet to be attached to the EXIOBASE model. For 'RoW' regions within EXIOBASE, capture fisheries production is summed across individual countries in the region before being assigned to the model. Within each country's or region's production, catches (and aquaculture production) are assigned solely to the sector "Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)". The resulting extensions are described in further detail within the Appendix. Extension sheets are prepared for each year between 1995 and 2014 to correspond to the EXIOBASE time-series. A set of environmentally-extended consumption-based data outputs (also present in the Appendix) are then compiled for this time-series via the EXIOBASE model using standard MRIO procedures (see, for example, Tukker et al., 2013) in order to provide a consumption-based "footprint" of fishery catch expressed in tonnes of landed catch and discards.

3. RESULTS

Figure 1a shows the consuming regions driving capture fishery harvest from 1995 to 2014. The global capture fisheries CBA has plateaued over the twenty-year time-series (at the global level, the total production and consumption based accounts are equivalent), which is in stark contrast to consumption of products from aquaculture. The unused extraction (discard) from capture fisheries is estimated to have a global average of 11.5% (11,755 kt) of the total catch (landed and discard) over the period 1995-2014 (Figure 1a, hatched area). It follows that unused extraction represents a significant component of the CBA, with this average roughly equivalent in mass to the calculated used extraction (landed catch) of the whole of Europe in 2014. Within the overall pattern of (relatively static) consumption, individual countries show rather different patterns. Consumption has increased in China (+75% over the timeseries), the rest of the Asia and Pacific region (+52%), and Africa (+70%), in contrast to consumption across Europe (-23%) and Japan (-47%), which have seen decreases in total consumption. Figure 1b indicates the CBA for capture fisheries consumption (used extraction only) scaled by national or regional GDP (at purchasing power parity), showing that for all countries consumption has been falling in comparison with total economic output. This trend is also apparent for many countries when consumption is compared with population size (Figure 1c), but in some regions (e.g. China, Remainder of Asia and Pacific, Remainder of America, Africa) consumption per capita has increased, or remained stable, over the time-series. Taking a global average, consumption activities were linked to 13.1 kg of (used) fisheries production per capita in 2014, plus a further 10.3 kg per capita from aquaculture.

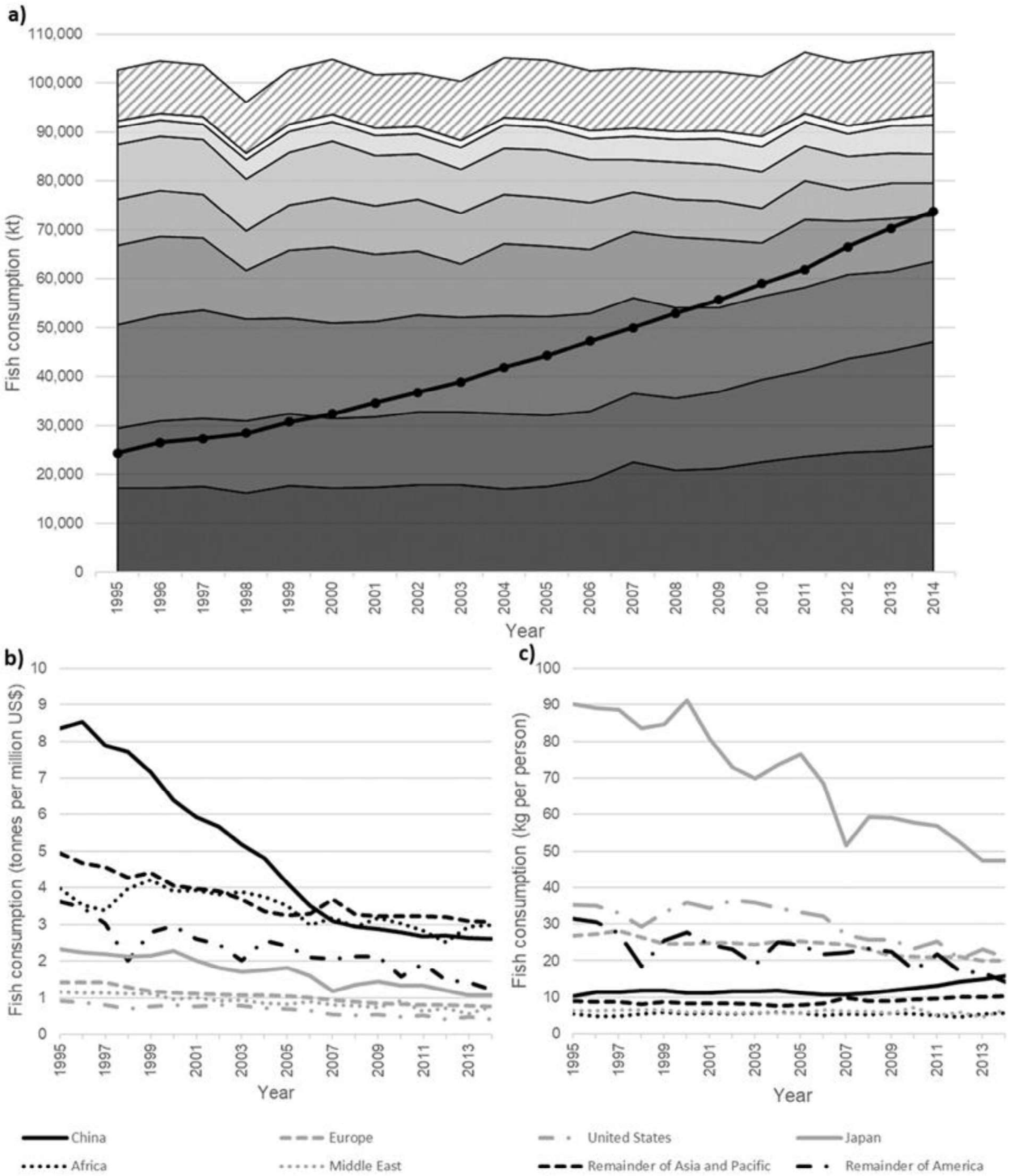

Figure 1. Global consumption based account of products of marine and inland fisheries between 1995 and 2014. a) Solid areas charted show CBA of used products from capture fisheries, in kilotonnes. Bottom-to-top are: 'Remainder of Asia and Pacific', China, 'Europe', 'Remainder of America', United States, Japan, 'Africa', 'Middle East'. Global discards from capture fisheries are shown in the hatched area. Plotted line shows global consumption of products from aquaculture. b) Consumption from capture fisheries (used extraction only) scaled by country or regional GDP at purchasing power parity (constant US$ 2010), tonnes per million US$. c) Consumption from capture fisheries (used extraction only) scaled by country or regional population, kilograms per person. Equivalent results for GDP-scaled and per capita aquaculture and combined consumption are included in the Appendix. For aggregated regions, the associated EXIOBASE classifications included are as follows: Middle East = 'RoW Middle East'; Africa = 'RoW Africa', 'South Africa';

Remainder of America = ‘RoW America’, ‘Mexico’, ‘Canada’, ‘Brazil’; Remainder of Asia and Pacific = ‘RoW Asia and Pacific’, ‘India’, ‘Indonesia’, ‘South Korea’, ‘Taiwan’, ‘Australia’; Europe = ‘RoW Europe’, EU 28 countries, ‘Turkey’, ‘Russia’, ‘Norway’, ‘Switzerland’.

If a country consumes more than it produces (i.e. catches) then it is a net ‘importer’ of fisheries products. Conversely, countries that produce more than they consume are net ‘exporters’. According to the results of the CBA, most countries/regions are net importers of capture fisheries products. Figure 2a presents the 1995 and 2014 balances (including discards) of consumption and production, in kilotonnes, for the top net importers and net exporters. The significant rise of China as a global importer is apparent here (which, along with South Korea, transitions to net importer by 2014 from a net exporter in 1995), as is the decrease in net imports of countries such as the USA and Japan. The ‘RoW Asia and Pacific’ region is the dominant global net exporter in 2014, whereas the ‘RoW America’ region was the world’s top net exporter in 1995. Figure 2b illustrates the top net importers and net exporters of fish captures associated with species of higher vulnerability, aggregating capture of species with vulnerability scores of greater than 60. These represent a relatively small proportion of global fisheries capture (6,847 kt out of 106,573 kt, or 6.4%, in 2014; down from 10,415 kt of 102,680 kt, or 10.1%, in 1995) but are likely of higher relative importance from a sustainable consumption point of view because fisheries targeting these species have lower intrinsic resistance to fishing pressure. China and Brazil are estimated to be the highest net importers in 2014 of fish products linked to these more vulnerable species (compared to the USA and Japan in 1995), whereas Norway and ‘RoW America’ are the largest net exporters at both the start and end of the time-series. Notably, whilst the overall consumption of fish with a vulnerability score of greater than 60 has decreased over the time-series, global consumption of fish with a vulnerability score of greater than 80 (i.e. highly vulnerable species) has increased between these years (from 306 kt to 1,401 kt). Full time-series information for trade balances, and the production/consumption values underlying Figure 2 are available in the Appendices.

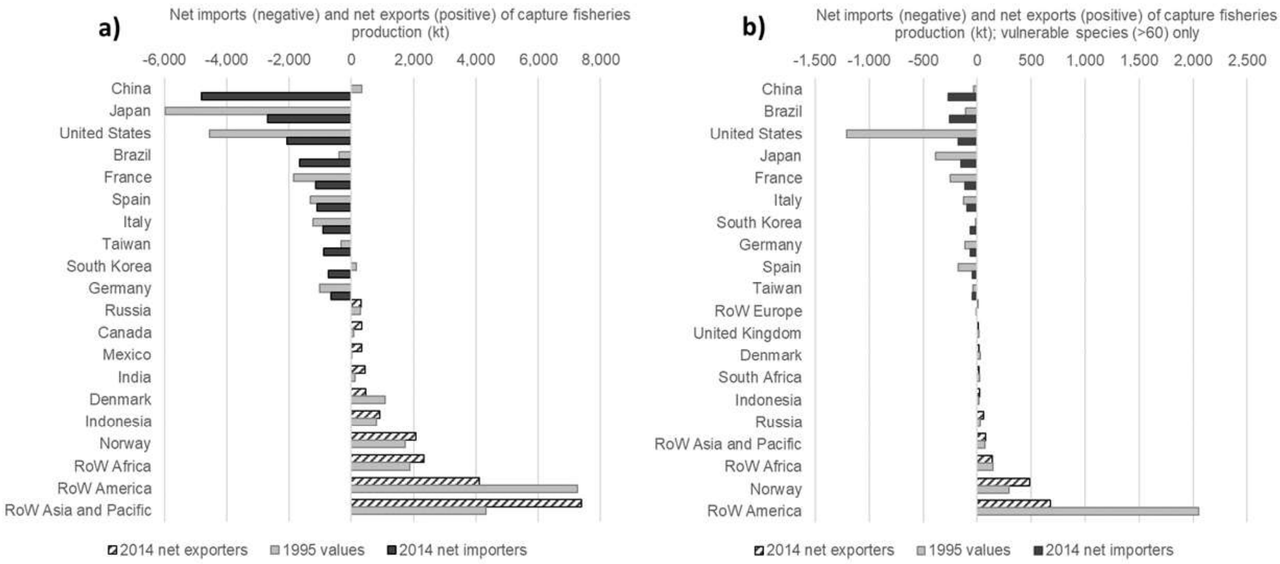

Figure 2. a) Top ten net importing regions and top ten net exporting regions of marine and inland fisheries production (including discards) in 2014 and equivalent values for 1995, kt, where 'importers' have overall production less than overall consumption according to the CBA and 'exporters' are the opposite. b) Top ten net importers and exporters for fisheries capture (including discards) of species classified with 'high-to-very-high' intrinsic vulnerability to fishing (vulnerability scores of 60-100; see Cheung et al., 2005) in 2014, and equivalent values for 1995, kt.

Over the time-series, there are significant changes in the capture locations of products embedded in the supply chains of global consumption. For example, for China (Figure 3a) there is a diversification in capture location, with a relative shift in production towards FAO areas Southeast Pacific and Western Central Pacific (among other areas) and a relative decrease in dependence on catches from the Northwest Pacific. In absolute terms, however, consumption from the Southeast Pacific, West Central Pacific, and Northwest Pacific has increased (by 704 kt; 1,819 kt; and 3,837 kt, respectively). In contrast, the USA (Figure 3b), has historically had a much more diverse sourcing structure but has shifted *away* from the Southeast Pacific area (with a corresponding absolute *decrease* of 2,795 kt between 1995 and 2014), whereas proportional capture activity in the Northwest Pacific has increased (although absolute consumption has remained similar from this region; a small increase of 182 kt). Results showing further connections between regions of production and consumption are provided in the Appendix. As the composition of species associated with fisheries consumption has changed, so accordingly have estimates of associated capture method. The USA, for example, has seen a significant shift away from species which are associated primarily with seine capture methods (Figure 3d), and a shift towards trawling - with bottom-trawling methods dominant. Conversely, China has seen a proportional shift towards species associated primarily with seine methods (Figure 3c) and captures associated with bottom trawling have proportionally decreased (replaced with species associated with unclassified trawling methods).

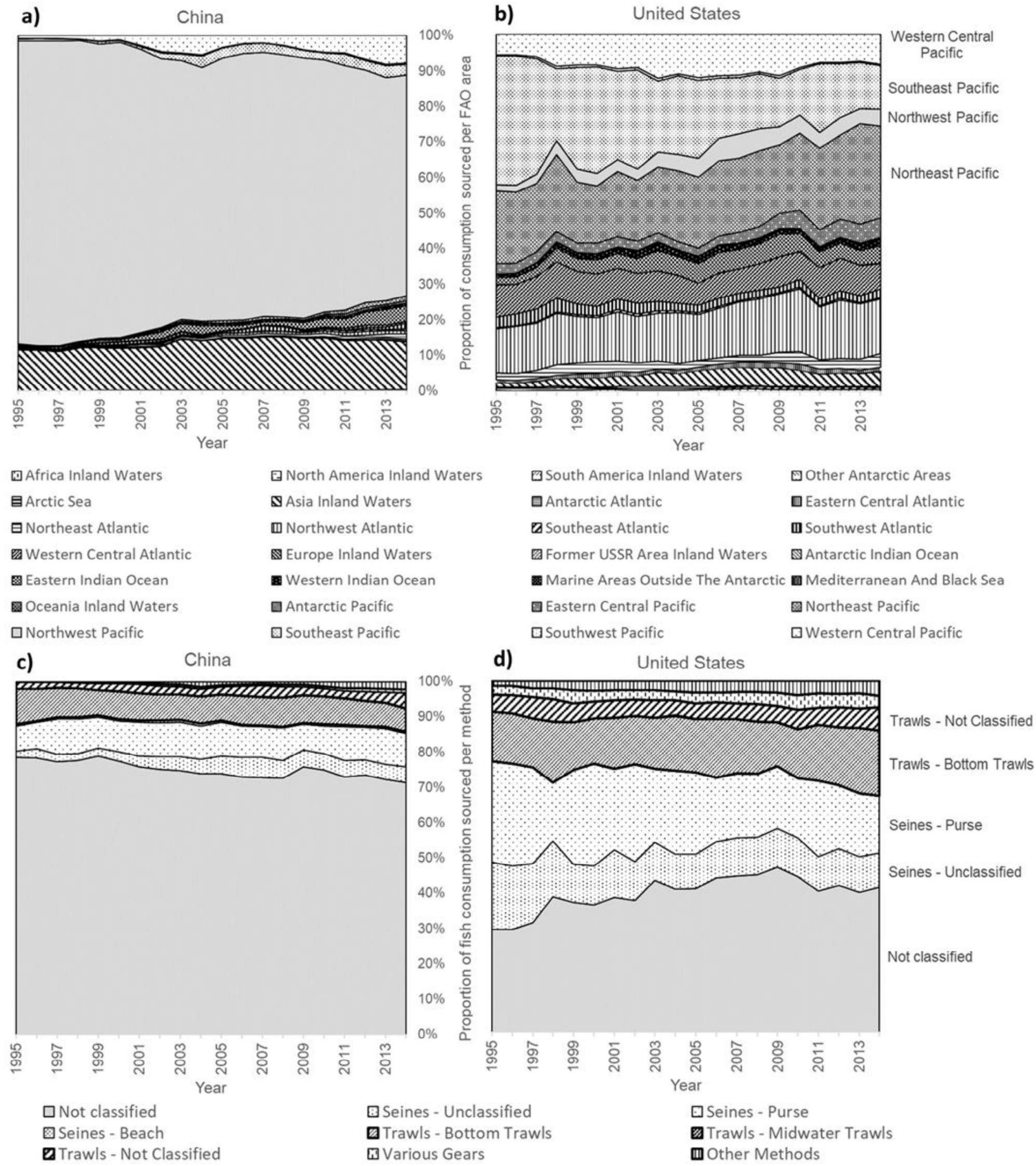

Figure 3. Proportion of consumption (including discards) sourced from different regions of capture (FAO Fishing Areas) for (a) China and (b) United States consumption, and proportion by main capture method associated with catches for (c) China and (d) United States. 'Bottom Trawls' aggregates bottom otter, pair and beam trawls; 'Other Methods' includes capture methods such as gillnets, hook-and-line, traps, and diving. Legends read from left to right correspond to plotted areas from bottom to top.

Of the species covered in the fisheries database, shrimp fisheries are associated with the highest discard rates and are thus the most 'wasteful' of the capture fisheries covered by our dataset.

Figure 4 shows two major producers of shrimp (which sit within the orders Reptantia and Natantia), with their capture distributed across major regions of consumption according to the CBA. There are striking differences in the distribution of consumption in these two examples, with the vast majority of production in China (the largest global producer across these species groups) embedded within its own consumption, in contrast to Canada (the fourth largest producer) which appears to have a highly diverse export market for its fisheries and is estimated to consume a relatively small proportion of its own catch.

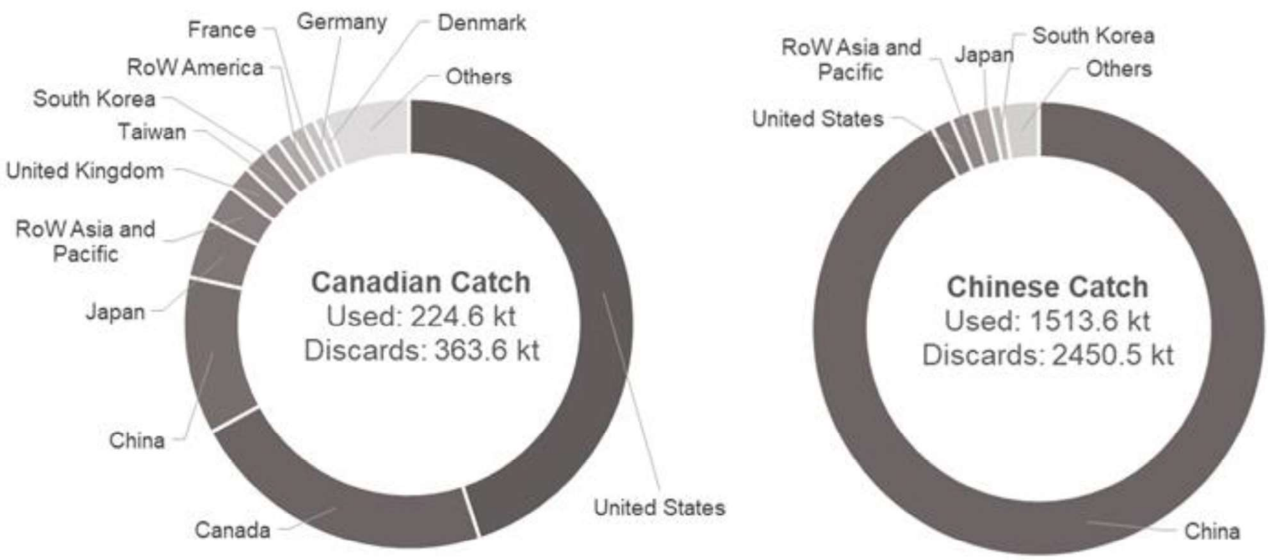

Figure 4. Consumption profiles of used and discarded extraction, kt, across two producers of the orders Natantia and Reptantia which are associated with high discard rates. China is the largest producer of these orders by mass, which are mainly associated with domestic consumption. Canada is the fourth largest producer of these orders, and has a more highly diversified export market.

4. DISCUSSION

Improving upon some of the limitations of previous attempts to encapsulate products of fisheries into material footprint assessments, this paper demonstrates the potential for a more comprehensive set of consumption-based accounts for capture fisheries, and one which is more relevant to the pressures imposed upon species and the environment. Using the most recent version of the EXIOBASE MRIO model, information available from selected fisheries-specific data repositories is utilised to highlight potential linkages to place-based production and threats to the sustainability of fisheries that have not previously been highlighted within global consumption-based studies. Below, results of this analysis are summarised, which highlight how they may offer additional insight into the sustainability of fisheries when compared to the aggregated information provided in previous studies. In recognition of the limitations associated with the presented implementation of the datasets, which includes a high level of ‘unclassified’ information in the results of the CBA, suggestions are provided for improving data compilation in future accounts which would likely significantly improve the accuracy - and therefore applicability - of results to inform sustainable consumption policy.

4.1. Contextualising results

Despite increased fishing effort (Bell et al., 2017), global capture from wild fisheries has plateaued and traditional material footprint based accounts that aggregate used and discarded fractions of capture could therefore give the impression that, overall, the footprint of capture fisheries is not a high priority. For example, our results (Figure 1b) indicate that consumption linked to capture fisheries is falling per unit of economic output across all world regions. This is particularly pertinent when considered in comparison with aquaculture production (or even hybridised fishery/farming systems; Klinger et al. 2013), which continues to expand (Figure 1a; FAO, 2016a) with rather different environmental concerns when compared with marine or inland capture fisheries (Pillay, 2004). FAO estimates that supply of fish products for human food consumption reached around 20kg per capita in 2014 (FAO 2016a). Due to the fact that our methods include consumption of fish products embedded in the full suite of consumption activities (which includes use not just directly for food, but also fish production embedded in feed products used in livestock and aquaculture industries, industrial products, and other goods and services), results from our CBA indicate that consumption activities are linked to 13.1 kg of (used) fisheries production per capita in 2014, plus a further 10.3 kg per capita from aquaculture, bringing total used consumption to 23.4 kg per capita. Results on the breakdown of this total consumption by key world regions align with FAO results, indicating that consumption from developing regions (e.g. Africa has a capture fisheries CBA of 5.6 kg per capita; total consumption, including aquaculture of 6.2 kg per capita) lags significantly behind developed countries (e.g. Japan 47.3 kg per capita from capture fisheries; 64.3 kg total) and China (which largely depends on products from aquaculture: 15.8 kg per capita from capture fisheries; 48.3 kg total) (Figure 1c and Appendix). For many countries where resource-efficiency based metrics and associated accounting methods are becoming more ubiquitous (for example in the EU; EEA, 2014; Moreno and García-Álvarez, 2018) overall consumption of capture based fisheries is undergoing decline (e.g. those in Europe, Figure 1a. Overall consumption in Europe is more stable, with demand increasingly met by aquaculture; see Appendix). With the adoption of initiatives such as the UN Sustainable Development Goals (UN, 2015), which assume ‘material footprints’ as key performance indicators (UN, 2016), more countries are starting to compile consumption-based accounting frameworks; an important development in the context of the changing profile of consumption markets for capture fisheries over recent years (Figures 1 and 2).

However, this material consumption perspective, whilst valid when assessing holistic material resource efficiencies associated with consumption, risks missing the rather more nuanced context of pressures that are associated with many products, including those of fisheries. As dependence on products of aquaculture increases, methods which allow disaggregated connections to be made between consumption activities and their sources and associated pressures are arguably even more relevant to ensure that continuing changes in consumption patterns and the nature of their links to individual ecosystems are not hidden to consumers via 'dilution' effects (Crona et al. 2016).

Figure 2 demonstrates the pitfalls of aggregating consumption estimates; analysis of more disaggregated information within this paper highlights that perceptions of consumers with the highest 'footprints' may vary markedly depending on the perspective adopted. For example, whilst China and Japan are the top two net importers of products of capture fisheries by total mass in 2014, an assessment limited to those species which have the highest levels of intrinsic vulnerability (as identified in the FishBase repository) indicates that Brazil rises to second place (with Japan dropping to fourth). Whilst over this time period the total global catch of identified vulnerable species (vulnerability score >60) has decreased, the catch of the most vulnerable species (vulnerability score >80) has actually increased, highlighting the importance of being able to disaggregate statistics to conservation-relevant scales. These alternative perspectives draw attention to the producers and consumers of fisheries linked to species which might be at higher risk of collapse from overfishing, and could direct greater attention to these supply chains within sustainable consumption policy and practice. The geographic context of production is important for similar reasons. Trade allows countries to substitute supplies from different stocks - a phenomenon likely reflected in our historical results (Figure 3) - so that consumption may remain unaffected by changes in any one ecosystem (Crona et al. 2016). Yet, the ability for countries to substitute sourcing locations will become limited as global production limits are reached (Deutsch et al. 2011). More detailed consumption based accounting for products of fisheries would allow a global assessment of shifting dependencies and substitution effects of this kind, providing potentially valuable insights into the drivers of, and responsibilities for, associated environmental effects. As illustrated by Watson et al. (2016) in analysis of trade in fisheries products, fish products are increasingly traded and have been subject to an expansion of trade routes over time. Developing countries are often net exporters of fish products, with developed countries net importers (Swartz et al., 2010). Similar results are indicated in our CBA analysis, with many developing regions of the world acting as net exporters (Figure 2) and diversification in sourcing regions for consumption apparent throughout the timeseries (Figure 3). Furthermore, whilst a consuming country may have relatively strong influence over fishing activities conducted within its Exclusive Economic Zone (EEZ), the management of waters in other areas of the world (and particularly international waters) may be harder to influence, potentially be subject to less stringent fisheries policy and poorer data collection, and may therefore be associated with less well-managed production (Mora et al. 2009;

Worm et al., 2009). For example, whilst overall US consumption of products from capture fisheries is decreasing, their relative dependence on products from marine areas such as the Northwest Pacific is increasing (Figure 3c). In turn, this consumption is associated with an increase in captured species which do not have classified capture methods in the utilised dataset (Figure 3d). Such data gaps (unless they can be overcome; see below) undermine the ability to assess the relative sustainability of shifting sourcing patterns. Diversification into new areas of production is not inherently negative if it reduces overall pressure on fish stocks that may have historically been overexploited, but this can only be determined if sufficient data is available to do so.

The destructive capacity of commercial capture fisheries has been well documented (e.g. Davies et al., 2009; Schratzberger et al., 2002; Watling and Norse, 1998) and, consequently, declines in overall material dependency do not necessarily align with declines in environmental impact. For example, landings can be maintained by increases in fishing effort, even as stocks decline (Thurstan et al., 2010), and greater swathes of the marine environment - including sensitive deep sea areas - are being targeted with relatively non-selective methods such as trawling (Clark et al., 2016). Incorporating analysis of the trends in capture methods (see for example Figure 3b and 3d) may therefore be as insightful in the assessment of the sustainability of consumption as details about mass (and material efficiency) alone. The ability to interrogate fisheries consumption statistics in finer detail is also important because many species with low overall mass-productivity are highly profitable. For example, many tuna species fetch high prices per kilogram and, as a result, continue to be targeted commercially despite dwindling stock sizes (Collette et al., 2011). While the ability to disaggregate to these taxonomic scales has previously been theoretically possible (due to aggregate material footprints being based on catch data which contains this specificity) this is the first time, to the authors' knowledge, that CBA analysis of fisheries has been attempted in such detail (e.g. Figure 4).

4.2. Limitations and recommendations for further work

4.2.1. Stock assessment and discard estimates

Whilst the results presented here highlight the need to look beyond conventional material-based accounts for fisheries products, the methods in this work are themselves subject to several limiting factors. Our outputs should therefore be treated as an improvement on current best practice, and as exemplars of the *potential* for consumption-based accounting for fisheries to be enhanced based on existing, accessible, data, rather than representing a comprehensive account of those necessary improvements. For example, within the FishBase repository, a number of species are associated with an 'unclassified' vulnerability assessment or capture-method information. Even where this data is present, the species-level information utilised from FishBase in this paper is typically only comprehensively available for a 'general' global stock, and does not vary temporally or spatially. However, the catch method or vulnerability of individual stocks is also important in fisheries management; one stock can potentially be depleted whilst others remain sustainably managed, and species can be harvested from the same, or different, regions of the sea using more or less damaging methods. The discard estimates utilised here - whilst offering improvements on previous best practice within consumption-based accounting - do not reflect the full diversity of discard rates that will occur across different fisheries and species groups in practice. Nor do they measure of any captured fisheries production (i.e. that reported in the FAO FishStat database) that is wasted after landing that would ideally also be classified as an ‘unused’ component of the fisheries economy. There are a number of datasets that provide opportunities to improve upon the integration of fisheries-linked information that a disaggregated CBA for fisheries would allow. The International Council for the Exploration of the Sea (ICES), for example, provides detailed stock assessments which could be linked to the regionally specific capture information provided in FAO. Indeed, spawning stock biomass information based on this repository has been assessed as providing a robust indicator for consumption-activity (Eisenmenger et al., 2016) in the form of ‘Fish catch outside safe biological limits’, which was compiled by EUROSTAT for reference years 1994 to 2010 (EU, 2012), but has recently been discontinued (pers. communication). A major limitation of the ICES stock assessments is that they are geographically limited to Northern Atlantic regions, which restricts their applicability in global assessments. However, the integration of similar regional stock assessments (for example, information in repositories such as RAM Legacy; Ricard et al., 2012) into consumption-based accounts is likely an avenue for further research.

Repositories of information such as *Sea Around Us* (Pauly and Zeller, 2015; Cashion et al. 2018; Zeller et al. 2018) have compiled estimates of capture methods and discard quantities across different species and regions/countries of capture. Whilst exploration of these datasets suggests they will not comprehensively cover all species and locations of capture covered by FishStat statistics, in combination with the FishBase repository they could be used to improve the integration of capture and discard information into consumption based accounts in future; for example for the development of more specific ‘Global Discard Indices’ for CBA (see Vázquez-Rowe et al. 2012b). They could also facilitate a broader assessment of the sustainability of fisheries, via the inclusion of more advanced methods of assessing pressure and impact linked to fisheries consumption, including estimating the fishing effort exerted across fisheries, more detailed vulnerability assessments (accounting for vulnerability of species beyond an assessment of life-history characteristics; Pinsky et al., 2011), or extension to include the wider range of impacts that might be associated with the use of varying fishing gears (including, for example, emissions associated with fishing fleets). Such advances must be weighed against the additional complexity and data-intensity that such improvements would entail, and therefore - as for all environmental assessments of this type - methods should be carefully designed with regard for the granularity of information that is sufficient to highlight, and respond to, consumption-driven pressures.

4.2.2. Economic allocations and material flows

The assignment of fisheries products to the economic data contained with the EXIOBASE model is also a point where potential improvements can be made. Whilst for inland fisheries it is reasonable to assume that the country of production and associated IO country-allocation are the same, for marine fisheries accurate allocation is more challenging. In FishStat, data is allocated to the country that flies the flag on the vessel, whereas the UN System of National Accounts (Galbis 1991; FAO 2004) states that the residence of the operator of the vessel should determine the economic allocations. However, at the current time there is no data collected at the international level that would allow a simple allocation of global capture production to countries of residence, and the "flag of the fishing vessel is the best available criterion for the assignment of nationality to catch and landings data" (FAO 2018). In the absence of internationally-available information that indicates which is the country of residence of a vessel, an assumption has been made within this study that this is the same as the country indicated by the vessel-flag. The extent to which this limitation impacts upon the 'correct' allocation of fish-capture-to-economy will vary on a fishery-by-fishery and country-by-country basis. However, it should be stressed that this assumption is also used where fisheries captures are encapsulated in the established material flow accounting methods on which this study is based, and therefore this limitation is also inherent in these aggregated accounts. In order to more comprehensively assess the connection between vessel-flag information, country of landing and country of ownership, vessel tracking information such as that compiled by Global Fishing Watch (Merten et al., 2016) could potentially be analysed. The most important consideration here is that the fishery data is consistent with both the economic activity data and bilateral trade relationships recorded in the MRIO in order to make a consistent link between the production and consumption accounts. This area is non-trivial to resolve, and similar issues can be seen in the allocation of bunker fuels when calculating carbon footprints (Usubiaga and Acosta-Fernández, 2015). For marine fisheries without additional information on the ownership and behaviour of fishing vessels, it is currently not possible to make an assessment as to the extent to which this biases our allocations.

For aggregated regions in the EXIOBASE model, the production associated with several countries' fishing fleets will be assigned to these and treated *en masse*, reducing significantly the resolution that exists in the underlying FAO data. Additionally, aggregating all fisheries products into a single sector means that trade linkages within the model treat all products homogeneously, disguising the fact that specific products will have different supply chains. Furthermore, EXIOBASE does not distinguish between the economic activity of capture fisheries and aquaculture, so average demand-side relationships are used. Whilst this issue is not unique to fisheries, and indeed is a problem to some degree with any MRIO-based consumption account (c.f. Lenzen et al. 2012), whose method of allocating species extinction threats to global consumption faces similar issues), for the presented results it does limit the ability to place certainty on the inter-country trades of specific species. Recent data and methodological advances in this field could help significantly in overcoming these issues. For example, in addition to the production information present within FishStat, trade data from FAO and UN Comtrade contain species-level information on the trade of fisheries products that might be utilised to allow more specific trade information to be integrated into consumption-based accounts (Swartz et al. 2010). In order to do this, additional work to convert this product-level trade information to ‘raw material equivalents’ would be necessary, with care taken to allocate production to trade information where mismatches exist (Watson et al. 2016) and allowances made for the fact that reported trade flows may also be affected by the problems of vessel ownership and reporting of catches described above. Such approaches have successfully been adopted in consumption-based accounts for terrestrial products (see, for example, Ewing et al., 2012; Stadler et al., 2018) and for fisheries within the context of a CBA which offers partial coverage of global economies (Guillen et al. 2018). Recent methodological advances, and increased data availability, have also demonstrated the potential to link sub-national trade information to global supply chain modelling (Godar et al., 2015; Croft et al., 2018). These advances could add valuable insight in cases where the ports associated with fisheries landing, and trade, are important determinants of trading routes and, thus, the final point of consumption.

4.3. Conclusions

This research highlights the potential for augmenting traditional material-based approaches with additional information associated with the pressures on the environment and species imposed by capture fisheries. It demonstrates how this may alter conclusions about the sustainability of fish consumption and, related to this, the consuming nations responsible for these pressures. Further, it is argued that existing methods and untapped datasets offer a rich source of material for significantly improving the development of more comprehensive, and robust, consumption based accounts for fisheries. Whilst the complexity of fishing systems, data gaps, and a lack of harmonisation mean that the implementation of new data into consumption-based accounting for fisheries is not without challenge, these offer the potential to adopt a more ‘nuanced’ approach to the assessment of consumption activities on the marine environment, which have historically been under-investigated in comparison with terrestrial production systems. These assessments are important within the context of policies and frameworks such as the EU’s Resource Efficiency agenda (EEA, 2014), or the framework of indicators developed for the Sustainable Development Goals (which includes general resource efficiency targets under Goal 12 ‘Ensure sustainable consumption and production patterns’, in addition to a number of targets linked to fishing activity under Goal 14 ‘Conserve and sustainably use the oceans, seas and marine resources for sustainable development’; UN, 2015).

The development of indicators that can provide insight across both production and consumption perspectives can help to ensure that policies developed with an eye to increasing the resource efficiency of consumer-markets are also cognisant of the broader sustainability of this activity. Even against a backdrop of global capture fisheries production that has plateaued in recent years, and declining material consumption in developed-country settings, overlooking the details of production-side pressures on the environment may threaten the long-term resilience of these systems which remain of significant social, economic and environmental importance globally.

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Appendices

A1a. R script for accessing FishBase and gathering extension data from species lists.

A1b. Example species list for use with R script, corresponding to species and other groups listed in FishStat capture data.

A2. Fisheries extensions, 1995-2014, landings (used extraction) and discards (unused extraction).

A3. Raw EXIOBASE outputs, 1995-2014, landings (used extraction) and discards (unused extraction).

A4. Time-series data of consumption per GDP and per capita for aquaculture and combined capture-aquaculture production.

A5. Time-series data of key net exporter and importers (that are illustrated in Figure 2), for all catches and catches of high vulnerability species.

A6. Absolute production and consumption for exporters and importers illustrated in Figure 2.

A7. Treemaps showing distribution of capture fisheries production from FAO Fishing Areas to countries and regions of consumption.

A8. Choropleths showing proportions of a country's capture fisheries consumption sourced from individual FAO Fishing Areas.

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Figure Captions

Figures as presented in main text - in Excel

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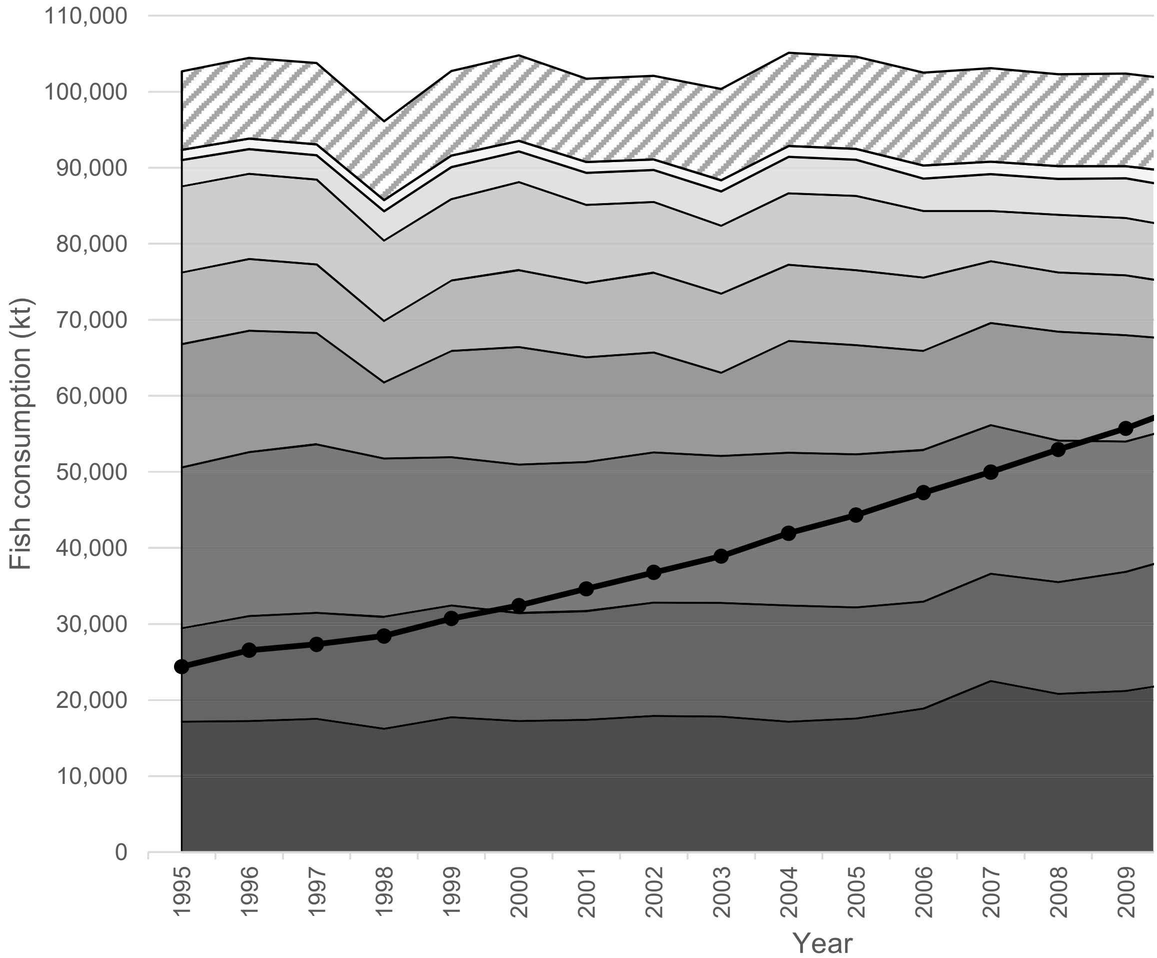

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2013	24879.37	20232.96	16344.44	10841.45	7316.193	6019.112	5638.22	1412.159
2014	25773.37	21439.64	16256.04	9382.87	6664.344	6022.777	5907.627	2013.354

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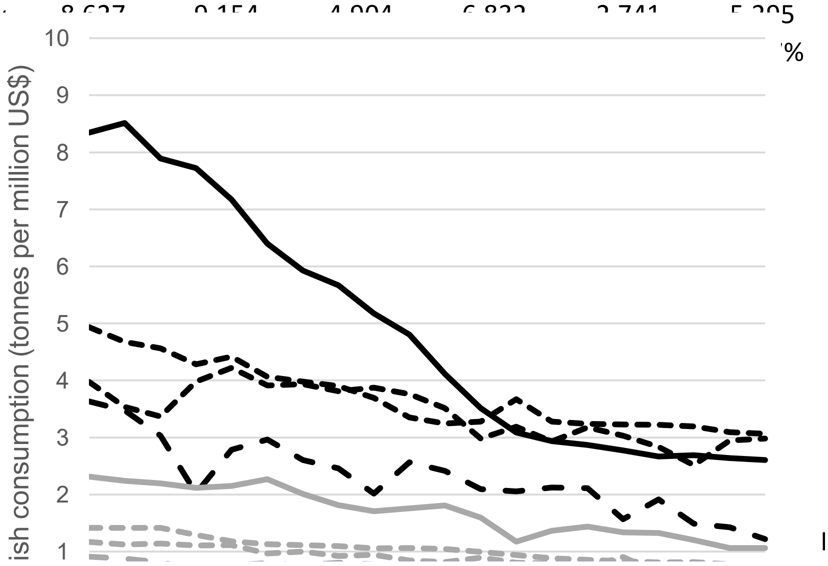

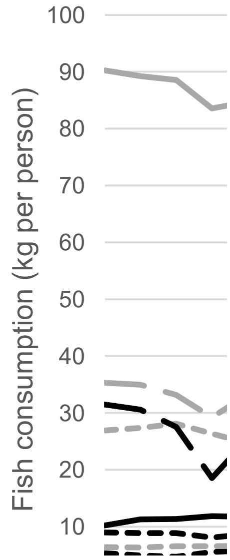

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Labels

Appendix 1a - R script

Click here to download Data File: West_etal_A1a_rscript_fishbasedata.r

Appendix 1b - species list (used in conjunction with R script)
Click here to download Data File: West_etal_A1b_specieslist.csv

Appendix 2 - fisheries extensions

Click here to download Data File: West_etal_A2_fisheriesextensions.xlsx

Appendix 3 - EXIOBASE outputs

Click here to download Data File: West_etal_A3_EXIOBASEoutput.xlsx

Appendix 4 - Additional per GDP and per Capita results

Click here to download Data File: West_etal_A4_perGDPperCapita.docx

Appendix 5 - net import and net export timeseries

Click here to download Data File: West_etal_A5_importexporttimeseries.docx

Appendix 6 - absolute consumption and production
Click here to download Data File: West_etal_A6_absconsprod.docx

Appendix 7 - treemaps

Appendix 8 - choropleths

Click here to download Data File: West_etal_A8_choropleths_shareofconsumptionbyFAOarea.docx