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Defining limits: What is ‘sustainable’ consumption?

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Summary

Unsustainable consumption and production patterns are at the root of the triple crises of climate change, biodiversity loss and pollution. All four governments of the UK have policies related to increasing the sustainability of our consumption at a national level, including via reducing our impacts overseas. However, there remains a lack of consensus around how to define environmentally 'sustainable' consumption. Whilst global temperature increase associated with carbon emissions has a widely accepted upper 'limit' of 1.5°C that actors are aiming to stay beneath, similar 'limits' for other impacts associated with consumption are less clear. This report aims to assess whether it is possible to set such global limits based on impartial scientific evidence (for example, through identification of key thresholds beyond which cascading ecological effects take place), or whether limits are necessarily subjective and reliant on the judgements of policymakers. It is based on a time-limited review of global limits that are defined and discussed within the scientific literature.

Widely used and accepted limits for the impact types assessed in the scientific literature include:

- A limit to biodiversity loss of 10 extinctions per million species per year or keeping 50–60% of Earth as largely intact natural ecosystems.
- A limit to global phosphorus inputs of 11 Tg P yr^{-1} to prevent oceanic eutrophication, or 6 Tg P yr^{-1} to prevent freshwater eutrophication.
- A limit to global nitrogen inputs of 62–82 Tg N yr^{-1} to prevent eutrophication.
- A limit to Material Footprint of 6–8 tonnes per person per year.
- A limit to global Ecological Footprint of one planet.

However, most of these limits are based on a combination of scientific evidence, assumptions, and value judgements, which can be difficult to disentangle. Whilst evidence is clear that increasing impacts against each of these variables has an increasingly negative impact on the planet and humanity, it is rare to find a specific global 'tipping point' that can be used as a scientific basis for setting a limit (N and P inputs being an exception at the local scale, with a clear point beyond which eutrophication occurs). Limits are therefore typically based on assumptions (for example, assumed future resource use by humans), particular philosophical positions (for example, the Planetary Boundaries framework takes a 'precautionary principle,' assuming that, as the conditions experienced within the Holocene are the only conditions that we know with certainty can support human life, that we should not exceed these), returning to a particular baseline year (for example, the Material Footprint 'limit' of six to eight tonnes per person per year is based on returning levels of consumption to an arbitrary baseline year of 1992), and value judgements (for example, relating to accepted levels of risk).

Other challenges to defining global limits include the spatial heterogeneity of impacts (for example, many areas of the world experience N and P deficits, so more nuance is needed than a single global figure), the masking of complexity (for example, limits set against specific impact types lead to a lack of holistic consideration of trade-offs across different impact types), and the translation of limits into policy. Additionally, the social implications of setting limits related to consumption were out of scope for this review, but we note the importance of taking these factors into account to ensure equitability in addressing issues related to consumption.

Nonetheless, the evidence is also clear that a well-defined and well-accepted limit can have significant impact in terms of galvanising action across diverse stakeholders. Therefore, whilst the current scientific evidence base struggles to help us define what limits should be, it also provides a clear steer that setting limits is useful when aiming to reduce the impacts

associated with consumption. Therefore, the lack of an accepted limit should not be used as a reason for inaction. Evidence can help to ground decisions (for example, highlighting the level of risk associated with differing levels of change) and to assess progress against any targets set, but the decision on where to draw the line (for example, how much risk is considered acceptable) needs to be taken subjectively in almost all cases. An effective limit relating to the sustainability of consumption will be simple and easy to communicate, cover multiple impact types, and take into account the effects of offshoring. Aligning with existing widely accepted limits, such as those listed above, has the advantage of bringing more stakeholders together towards a common goal, which makes it more likely to succeed than fragmented action.

Contents

1. Introduction

1.1. Policy context

Unsustainable consumption and production patterns are at the root of the triple crises of climate change, biodiversity loss and pollution (IPBES 2019; IPCC 2023; One Planet Network 2024). International goals and targets aim to address unsustainable consumption and production globally, including Sustainable Development Goal (SDG) 12 (to "ensure sustainable consumption and production patterns"), and the Kunming-Montreal Global Biodiversity Framework (GBF) Target 16 (to "reduce the global footprint of consumption in an equitable manner"). Further, all four governments of the UK have policies around increasing the sustainability of our consumption at a national level, including via reducing our impacts overseas:

- England's 25 Year Environment Plan aims to "avoid improving our domestic environment at the expense of the environment globally" and its first update, the Environmental Improvement Plan, recognises that "the impact of our use of resources extends beyond our borders", and includes targets and commitments around shifting to more sustainable supply chains (although noting that these were published under the previous conservative government).
- Wales' 2015 Wellbeing of Future Generations Act has a goal for "a globally responsible Wales," which includes "ensuring that our supply chains are fair, ethical and sustainable," "supporting sustainable behaviour," and "efficient use of resources."
- Scotland's 2020 Environment Strategy includes an outcome that "we are responsible global citizens with a sustainable international footprint."
- Northern Ireland's Sustainable Development Strategy has a guiding principle of "living within environmental limits."

However, while it is internationally recognised that we must limit global temperature increases to 1.5°C to avoid the most catastrophic impacts of climate change, other proposed limits to impacts associated with unsustainable consumption and production are not as widely accepted or incorporated into policy. Some quantitative targets related to consumption and production have been set (such as halving global food waste – included in both SDG 12 and GBF Target 16), but these are rarely linked to limits or thresholds which, if crossed, may move Earth systems outside of safe states, with potentially harmful effects for humans. Understanding such limits is critical to assessing existing targets and setting new targets that are sufficient to move humanity into 'safe operating spaces' (Rockström *et al*. 2009; Steffen *et al*. 2015).

A broad range of methods are used to define the 'limit' of how much unsustainable consumption is too much. Boundaries and thresholds may be decided based on a combination of factors, including scientific evidence, application of the precautionary principle (e.g. used in Planetary Boundaries, the GBF), and willingness of politicians (e.g. the GBF). Science may be used in the context of limits to identify a tipping point, beyond which non-linear dynamics lead to significant changes in an ecosystem's structure or function, or to estimate ecosystem service provision (or lack thereof) under varying scenarios, against which value- and risk-based decisions can be taken, thereby combining a scientific understanding of consequences with value judgement on acceptability (Usubiaga-Liaño & Ekins 2021). This paper summarises relevant literature on this topic by explaining the scientific basis of proposed limits, with a focus on approaches that could be used in the UK.

1.2. Aims and scope

This report is based on a review of both scientific and grey literature aiming to identify proposed frameworks and limits for sustainable consumption, their scientific basis and underlying rationale.

The scope of the review was limited to identifying proposed frameworks and limits and understanding their basis in environmental or Earth systems sciences. Therefore, while it is important to also consider the social implications of goals around sustainable consumption (for example, by identifying social baselines for consumption, rather than upper thresholds alone, or by understanding the behavioural psychology behind how people might engage with different levels of ambition regarding limits), this was not covered as part of this review. The focus of the review is on relevance to national scale policy, so work done in the context of defining limits for individual companies (e.g. the Science Based Targets Network) was also out of scope.

The review was time limited and did not aim to be comprehensive or systematic. Rather, it focused on key literature in this area and approaches that could be used in the UK. The frameworks and impact types included are the Planetary Boundaries framework, biodiversity loss, biogeochemical flows (particularly nitrogen and phosphorus cycles), material extraction (measured by Material Footprint), and ecological footprint These impact types, related frameworks and metrics were prioritised because they have a high profile internationally and have been subject to widespread scrutiny, and because (based on discussion with representatives across the four UK governments) they are relevant to the UK context. However, many other relevant frameworks and impact types, such as the ESGAP framework (Usubiaga-Liaño & Ekins 2021), and water use or aerosol loading, have not been covered in this review due to its time-limited nature.

The review did not aim to provide details on how proposed limits could be incorporated into policy at the national or subnational level. Instead, the aim was to highlight available options and explain their underlying rationale. Further work to understand the social implications of proposed thresholds (e.g. considering the social boundaries identified in the ‘doughnut economics’ concept) and how to appropriately apply targets in a UK context would be valuable complementary research.

The review starts with consideration of what makes a useful limit (Section 2), then explores a range of limits and frameworks proposed within the literature (Section 3), before synthesising the key challenges and opportunities that this presents (Section 4) and concluding on the implications of this for policymakers (Section 5). Appendix 1 also considers the relevance of this work to JNCC’s existing work on the Global Environmental Impacts of Consumption (GEIC) indicator. Assessment of the evidence base beyond GEIC for measuring against any target set using indicators was not included within scope but has been covered in other recent reports (Jennings *et al*. 2024; Carr & Peake 2024).

1.3. Disclaimer

This report does not aim to make specific recommendations about which limits should be adopted; nor does it constitute any kind of suggestion or commitment that any of the thresholds mentioned will be incorporated into policy. Rather, it aims to act as an information source that, alongside other information, could be used by policy makers considering policies to improve the sustainability of consumption. JNCC’s mission is to be an impartial scientific authority on UK and international nature conservation. As a public body, we advise governments, and work in partnership with business and society.

2. What makes a useful limit?

Internationally, the most widely accepted threshold associated with the impacts of consumption and production is the 1.5°C limit to climate change. This section therefore explores what makes a useful limit, with a particular focus on this limit as an example that can be learnt from.

Since the 2015 Paris Agreement, countries have agreed to keep "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C". In 2015, the science on a 1.5°C warming limit was "less robust than for the 2°C warming limit or warming beyond this limit" (UNFCCC 2015), and the Paris Agreement called on the Intergovernmental Panel on Climate Change (IPCC) to provide a Special Report on the impacts of temperature increases of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, which was published in 2018. The report found that numerous climate-related risks for humans and nature would be greater with 2°C of warming (as well as with mitigation pathways temporarily overshooting 1.5°C, even if they return to 1.5°C later in the century) compared to 1.5°C of warming (Hoegh-Guldberg *et al*. 2018). It also found that many risks are greater with 1.5°C of warming compared to present-day levels.

The process of generating this evidence base, and its subsequent adoption internationally (such as in the UK Government's 2030 Strategic framework for international climate and nature action) was strongly driven by political processes. Political willingness, practical considerations and value judgements about acceptable levels of risk contributed to agreement to the 1.5°C threshold. The science demonstrated clear risks associated with a 1.5°C increase, though these risks are reduced compared to a 2°C increase, and this formed the basis of more subjective discussions around what was considered an acceptable level of risk.

To assess proposed limits such as the 1.5°C temperature threshold, it is worth considering those elements that make them 'useful' in the sense of being likely to direct action effectively to reduce negative environmental impacts of consumption and production. For example, where possible:

- Limits should be grounded in evidence (SBTN 2024).
- Limits should include embedded consumption and production so that impacts cannot be offshored (Carr & Peake 2024). For example, accounting for the energy consumption of a given country must include the energy produced and used domestically, as well as energy use associated with imported products that are consumed in that country (Ritchie 2021).
- Multiple impact types should be considered holistically, to avoid shifting environmental burdens from one impact type to another (Usubiaga-Liaño & Ekins 2021). For example, a reduction in carbon emissions could result in an increase in other types of environmental harm (Laurent *et al*. 2012).
- For applications in a policy context, limits that are conceptually simple, meaningful and linked to national policies are more likely to be adopted (Jennings *et al*. 2024), and those that can be quantitatively linked to actions are more likely to be successfully implemented (SBTN 2024).
- Data should be available to measure whether we are within or have transgressed limits, and to measure progress towards targets set in relation to them (Jennings *et al*. 2024).

In this sense, the 1.5°C limit can be described as useful on several fronts, including its grounding in scientific evidence, its conceptual simplicity (e.g. setting a threshold of temperature, which is meaningful to most people, rather than concentration of CO_2 or energy at the Earth's surface in W/m^2 – although this has to go alongside education around why a temperature limit is necessary), its links to a multitude of human activities (e.g. it can be used to direct action to reduce greenhouse gas emissions from different industries), and, notably, the broad consensus that it was able to gain. However, as it focuses on one impact type, considering the 1.5°C limit in isolation risks environmental burdens to other impact types.

Despite climate change being only one of many harmful environmental impacts of consumption and production, thresholds proposed for other impact types have not been as widely accepted as the 1.5°C limit. The next section of this report will assess other proposed frameworks and limits to the impacts of consumption, in particular by reviewing the scientific evidence underpinning them.

3. Environmental impacts of consumption: proposed frameworks and limits

This section will explore proposed frameworks and limits to the impacts of consumption. It begins with an overview of perhaps the best-known framework for understanding human impacts on the Earth system: the Planetary Boundaries framework, which includes nine impact types. It then moves on to explore four impact types and proposed limits that came up commonly in the literature review: biodiversity loss, biogeochemical flows (both of which are included in the Planetary Boundaries framework but are also assessed more holistically against other evidence sources available), material extraction as measured by Material Footprint, and ecological footprint.

3.1. The Planetary Boundaries framework

In Europe, the Planetary Boundaries framework has been perhaps the most influential framework for understanding environmental limits to the Earth system and how human activities may move us beyond these limits – outside of 'safe operating spaces' – and has been incorporated into some national policies (Hurley & Tittensor 2020). The framework was first developed by Rockström *et al*. (2009), and has been subsequently updated (Richardson *et al*. 2023; Steffen *et al*. 2015) and incorporated into other research (e.g. Dasgupta 2021; O'Neill *et al*. 2018) and frameworks such as Doughnut Economics (Raworth 2017).

The Planetary Boundaries framework emerged from the large body of research which shows that human activities, particularly since the mid-20th century, are pushing components of the Earth system (for example, climatic conditions) outside of the relatively stable states of the preceding ~11,700 years of the Holocene epoch (Richardson *et al*. 2023; Rockström *et al*. 2009; Steffen *et al*. 2015). As the conditions of the Holocene represent the only state of the planet that we are certain can support contemporary human societies, the authors apply the precautionary principle, arguing that we should avoid pushing the Earth system out of this state and into a state likely to be less hospitable for humanity. The Planetary Boundaries framework includes proposed boundaries, or limits, to nine different Earth-system processes which, if crossed, increase the risk of pushing the Earth system outside of the Holocene-like conditions which represent the safe operating space for humanity. The most recent update by Richardson *et al*. (2023) determined that we are currently transgressing six of the nine identified Planetary Boundaries (Figure 1).

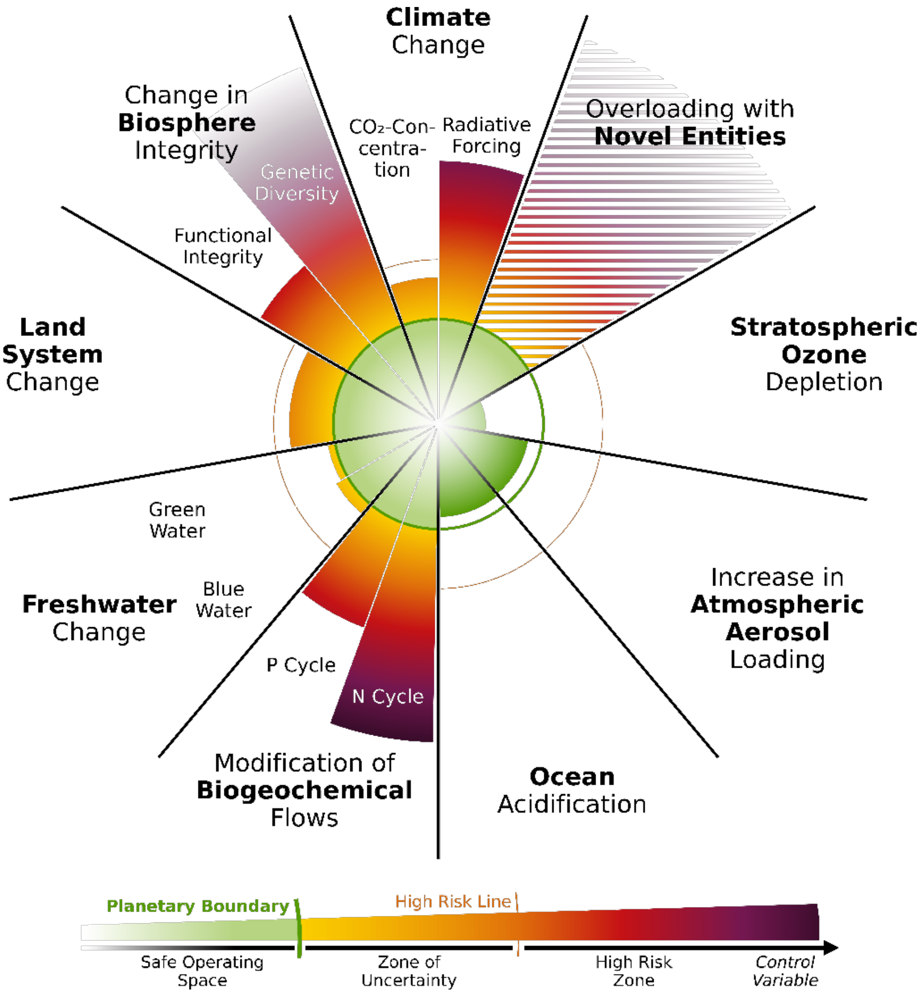

Figure 1. Current status of control variables for all nine Planetary Boundaries, reproduced from Potsdam Institute for Climate Impact Research (PIK) (https://www.pik-potsdam.de/en/output/infodesk/planetary-boundaries/images under CC BY 4.0 license). PIK adapted the image from Richardson *et al*. (2023). The green zone is the safe operating space (i.e. the zone below the safe limit). Purple represents the high-risk zone, where there is high confidence that boundaries have been transgressed. Results are normalised so that the centre represents mean conditions in the Holocene, and the Planetary Boundary is located the same distance from the centre for each variable.

3.1.1. How are Planetary Boundaries determined?

Planetary Boundaries are based on scientific evidence related to how the risks of impacts for humanity increase as Earth system processes are further perturbed (Steffen *et al*. 2015). Not all the Earth system processes included in the Planetary Boundaries framework have global tipping points – though for some it is thought that tipping points (at global-, continental-, ocean basin-, or regional-level) exist. Therefore, not all have singular thresholds. However, even for those processes that have singular thresholds, the Planetary Boundary is set upstream of this (i.e. there is a buffer between the boundary and the biophysical threshold, which the authors argue is to account for scientific uncertainty and allow time for society to act before the threshold is crossed).

All the Planetary Boundaries are set at the lower edge of a 'zone of increasing risk', representing a limit below which current research suggests (while acknowledging scientific uncertainties) that the risk of substantially moving the Earth system outside of a Holocene-like state is very low (Figure 1). In most cases, the boundary value is higher than the observed range through the Holocene up to the Industrial Revolution, due to evidence about buffering and resilience of the Earth system, though the authors also note that this resilience may decrease if Planetary Boundaries are surpassed further (Richardson *et al*. 2023). Therefore, both scientific evidence and value judgements about degrees of acceptable risk (made by scientists – there was no consultation with stakeholders or the public) were involved in the setting of Planetary Boundaries. Further details about how boundaries are set for each Earth system process are given in Richardson *et al*. (2023) (and earlier publications: Rockström *et al*. 2009; Steffen *et al*. 2015), and the boundaries relating to biodiversity loss and biogeochemical flows are discussed in more detail later in this report (Sections 3.2 and 3.3).

It should also be noted that the boundaries are data-limited, and in some cases based on evidence from systems that only partially relate to the overarching 'boundary area'. For example, the 'land system change' boundary refers to the area of forested land as the percentage of original forest cover, rather than to all land systems.

3.1.2. Discussion of the Planetary Boundaries framework

Biermann and Kim (2020) summarise several criticisms of the Planetary Boundaries framework. For example, the validity of the subjective judgements about the degree of acceptable risk made by scientists has been questioned. These judgements have been made by a narrow group who are overwhelmingly based in the Global North (whereas many of the worst impacts of perturbations of Earth system processes will be experienced in the Global South) without public participation or stakeholder engagement. Further, the Planetary Boundaries have been criticised for being too long-term focused, incomplete (e.g. marine systems are poorly represented), and for not aligning with decision-making scales (e.g. national or regional; Usubiaga-Liaño & Ekins 2021) – though note that there have been attempts to downscale Planetary Boundaries (e.g. O'Neill *et al*. 2018), as discussed later in this report (Section 4). Some specific boundaries have been identified as being not strict enough or inadequately defined and some alternatives have been proposed, for example Net Primary Production (biomass produced by plants) was proposed as an alternative in response to Rockström *et al*. (2009)'s original framework (Running 2012), and has been incorporated as a metric of biosphere integrity in the latest framework (Richardson *et al*. 2023).

The other broad approach to defining and measuring the environmental impacts of consumption consists of environmental footprint metrics like the Ecological Footprint, carbon footprint, nitrogen footprint, and Material Footprint (explored in Sections 3.2–3.5). These are measures of specific consumption impacts and are not always associated with clearly defined limits, though footprint limits can be set. As environmental footprint metrics focus on a singular impact type, they could result in shifting environmental burdens to other impact types (Laurent *et al*. 2012). Meanwhile, the Planetary Boundaries framework is more holistic and enables consideration of interactions between different impact types (though the authors acknowledge that understanding and accounting for boundary interactions in policy remains a challenge; Richardson *et al*. 2023; Steffen *et al*. 2015). There are several proposed ways of synthesising environmental footprints and Planetary Boundaries, which could help overcome some of the limitations of each (Fang *et al*. 2015; O'Neill *et al*. 2018; Vanham *et al*. 2019). For example, aiming to stay within Planetary Boundaries may be one way of calculating appropriate limits to environmental footprints (Fang *et al*. 2015; O'Neill *et al*. 2018).

3.1.3. Planetary Boundaries: conclusions and recommendations

The Planetary Boundaries framework defines a 'safe operating space' for humanity based on stable Holocene-like conditions, and proposed limits to nine key processes which, if surpassed, are likely to push the Earth system outside of this stable state. Planetary Boundaries have been determined based on both scientific evidence and value judgements made by scientists about levels of acceptable risk, with each boundary set at the lower edge of a 'zone of increasing risk'.

Those considering setting targets related to Planetary Boundaries should note that:

- Planetary Boundaries have been determined based on scientific evidence and value judgements. These value judgements reflect the perspectives of those researchers behind the Planetary Boundaries framework (rather than being developed in consultation with stakeholders, or with public participation).
- The Planetary Boundaries framework has been widely praised and has been influential in research and incorporated into national policies (particularly in Europe). However, there have also been criticisms of Planetary Boundaries and, while more holistic than other approaches which focus on single impact types, the framework and boundaries as they are currently defined should not be considered complete or final. For example, data gaps prevent full representativeness (both within each boundary, and in the context of which boundaries are included within the suite available).
- Interactions and trade-offs between different boundaries (and between boundaries and other environmental impact types) should be considered to avoid shifting environmental burdens to other impact types.
- Considering Planetary Boundaries alongside complementary frameworks and metrics, such as environmental footprint metrics, may be an effective way to direct action around consumption and production at sub-global scales.

3.2. Biodiversity loss

Biodiversity loss can be measured in numerous ways, including the sum loss of individuals and/or species, loss of genetic diversity or loss of functional diversity. The rate of species loss that has occurred during the Anthropocene (the most recent time period during which humans have had a substantial impact on Earth) has led many scientists to refer to this period as the sixth mass extinction (Pievani 2014). There is strong evidence indicating that this recent biodiversity loss is largely human-driven, primarily caused by over-harvesting and land use change for urbanisation and agriculture to support consumption – making it the first mass extinction to be caused by a single species. As an example, in the UK in 2022, consumption was estimated to be associated with the future loss of four species worldwide (SEI/JNCC 2023 – LIFE metric; see further discussion of this metric in Appendix 1).

Studies of previous mass extinctions demonstrate the integral part that biodiversity plays in maintaining Earth and ecological processes, making this one of the two 'core planetary boundaries' (Rockström *et al.* 2009). Controlled experiments which manipulate biodiversity show that biodiversity complexity is a variable that has a significant effect on many ecosystem functions, such as nutrient cycling and biomass production (Cardinale *et al.* 2011; Stachowicz *et al*. 2007; Balvanera *et al*. 2006; Cardinale *et al.* 2006). Healthy ecosystem functioning is vital to provide ecosystem services on which humans depend (Cardinale *et al*. 2011; Stachowicz *et al*. 2007; Balvanera *et al*. 2006; Cardinale *et al.* 2006). Maintaining a complex and diverse biological community also increases the resilience and adaptability of ecological systems to disturbances (Diaz *et al.* 2005), and buffers against shift changes and tipping points. Therefore, the loss of biodiversity, due in large part to overconsumption and its associated activities, could lead to significant, non-linear, irreversible changes.

Preserving biodiversity is therefore important to both preserve healthy ecosystem functioning and to retain ecosystems' resilience to change. The inherent complexity and diversity of biological communities at varying scales means that there are numerous ways to measure the different levels of diversity that they have – and lose. This means that deriving a single universal global indicator can be complex, and compromise may need to be made in terms of which aspects of biodiversity are included. Similarly, differences between terrestrial and marine biodiversity should be acknowledged, with many metrics largely focusing on terrestrial biodiversity.

3.2.1. Proposed limits to biodiversity loss, and discussion

A number of different types of limits to biodiversity loss have been proposed in the literature, each focusing on a different aspect and role of biodiversity, with no clear consensus on one measure which is more suitable to use as a global limit than others. Measures of biodiversity loss on which limits are based include extinction rates and the Biodiversity Intactness Index (BII). Other metrics sometimes used in the literature as proxies to represent biodiversity loss include human appropriation of the biosphere's NPP (HANPP) and the area of protected or intact ecosystems. This section will explore the limits, justifications and critiques of each.

Rockström *et al*. (2009) included discussions of a biodiversity loss threshold in the original Planetary Boundaries framework. They note that, despite its importance, there are difficulties in measuring a threshold for the regulatory role of biodiversity at a global level. Instead, the authors suggest an interim indicator based on extinction rates, which can be estimated more readily and for which we have good historical data. The fossil record provides estimates of historic extinction rates, and the background extinction rates during the Holocene represent the acceptable level of extinction that continue to allow for the maintenance of complex ecosystem functioning and resilience that we know can support human life. The background rate of extinction varies between taxonomic group, but the widely accepted rate across multiple taxa on which we can base human impact is one E/MSY (one extinction per million species per year; Pimm *et al*. 2006). Rockström estimates that a global boundary should limit the extinction rate to under 10 E/MSY, with a ten-fold confidence interval (10–100 E/MSY). It is important to note that there is little scientific backing to these thresholds and Rockström suggests that it may be unlikely that there is a threshold which, if crossed, would result in rapid, significant and irreversible change (i.e. a single biodiversity tipping point – though such tipping points likely exist for certain taxa in certain ecosystems; see Lenton *et al*. 2023). Despite this, Rockström's threshold has been largely agreed upon in the wider literature, and has been retained in later updates of the planetary boundaries framework (Richardson *et al.* 2023; Steffen *et al.* 2015).

Although using extinction rates is relatively easy to communicate to the public, it also has some major limitations. Pimm *et al.* (2006) highlight how a focus on species extinctions will underestimate the impact that humans have, as many areas experience high levels of local extinctions, the effect of which are overlooked when the species survive elsewhere (unless considering regional extinction rates). Similarly, areas may experience high levels of population declines to a point where the species no longer contribute to the functioning of an ecosystem (and thus becomes functionally extinct), but some individuals remain present. Likewise, there is often a time-lag between when a species becomes extinct (or is rediscovered) and when they are formally reported as so. To measure the true impact of population declines, Şekercioğlu *et al.* (2004) suggest measuring species which are "extinction prone" and "functionally extinct."

Rockström *et al.* further highlight the fact that using a metric like extinction rate that treats all species equally is an oversimplification, as species differ significantly in the impact that they have on an ecosystem. For example, the loss of keystone species, such as an apex predator or a structurally important species, will potentially cause shifts in whole ecosystem structure and communities with the loss of a single species. It is therefore the species composition and interactions between species that must be preserved, rather than simply aiming to preserve as many species as possible (Diaz *et al.* 2005). Faith (2015) suggests that thresholds could capture the importance of maintaining species with multiple different features and roles by focusing on phylogenetic diversity, which aims to conserve species with a wide range of features and niches so that they have the adaptability to respond to the unknown future changes in ecosystems to continue promoting their functioning. Extinction rates often focus on vertebrate species loss, which is an unrepresentative sample of global biodiversity, accounting for less than 2% of species, and excludes many of these key ecosystem functions (Mace *et al*. 2014).

To account for the functional role of biodiversity in ecosystems, the Steffen *et al*. (2015) update to the Planetary Boundary framework added a functional diversity boundary to complement the extinction rate boundary (now known as the 'genetic diversity' boundary). The rationale of this amendment was to emphasise the two main roles of maintaining biodiversity:

1) maintaining genetic diversity to allow continuing evolution with changing environments and the persistence of species and ecosystem functions, and
2) the role of biodiversity in delivering these functions. Functional diversity should take into account the abundance, value and distribution of functional traits.

Although there are ways to do this at smaller scales, obtaining a global threshold for functional diversity is challenging. As an interim indicator, the authors proposed use of the Biodiversity Intactness Index (BII), which uses estimations of the ecosystem-level pre-industrial abundance of a range of taxonomic and functional groups to assess their changes following human activities, such as land use change to support consumption.

The BII covers a large number of species from a range of taxonomic groups. Scholes and Biggs (2005) demonstrated how decreasing BII can correlate with increasing habitat degradation across seven African countries, suggesting that it could be a powerful tool to measure biodiversity loss. However, a general lack of evidence for this relationship led Steffen *et al.* (2015) to propose a preliminary threshold of a BII score of 90%, with a large range of uncertainty of 90–30%, indicating the need for more evidence to support a threshold that prevents shifts in Earth systems. Additionally, calculating BII relies on expert knowledge at local/regional/ecosystem scales, which is not always available, especially for the oceans, potentially further limiting its use until more evidence is made available. Finally, Richardson *et al.* (2023) note that BII does not directly link to biogeochemical and energy flows, which is needed for global limits. Therefore, BII shows promise as a measure to establish global limits in the region of 90%. However, there needs to be further research to facilitate the knowledge gain that is required to make this applicable to all regions and scales.

Richardson *et al*. (2023) redefined the functional diversity boundary as "a limit to the human appropriation of the biosphere's net primary production (HANPP – Human Appropriation of Net Primary Production)," against a Holocene benchmark which was markedly stable up until the 1800s. Net primary production (NPP) refers to the "energy and materials flow into the biosphere" as a measurable proxy of photosynthesis – a vital process that underpins ecosystem functioning and services (although not truly a measure of functional biodiversity *per se*). Therefore, this boundary measures how much of the potential NPP is harvested or altered by human actions and aims to ensure that directing energy flows into human consumption will not substantially affect the energy flows into the biosphere which is needed to maintain its health and functioning. Due to the declines in the biosphere since the industrial revolution, a time that also saw a marked increase in HANPP, it is likely that the current HANPP has already crossed a boundary (Richardson *et al*. 2023). Given that the industrial revolution saw a large increase in HANPP, Richardson *et al.* argue that the HANPP boundary should coincide with the increase witnessed during the late 19th century and therefore suggest that the boundary should be set to 10% of the stable Holocene levels. However, it is important to note major changes in context since that point in terms of human population levels and consumption standards. Haberl *et al.* (2014) support the adoption of NPP as a biosphere boundary, stating that it has a large dataset supporting its use and application, and that it combines many of the defined Planetary Boundary variables. Krausmann *et al.* (2013) also offer support for using HANPP as a proxy for human's effect on the biosphere, noting its use as a tool to establish limits on the amount of biomass that humans can extract from the biosphere.

Some other studies advocate for a global limit based on the area of protected or intact ecosystems in order to protect sufficient biodiversity and support global processes. This approach recognises the importance of protecting and conserving community structure and interactions rather than a target number of species, for example by quantifying limits of land area to be protected. The concept of setting targets for the proportion of the Earth protected for biodiversity conservation is now widespread and an integral part to many national and international targets. For example, the Kunming-Montreal Global Biodiversity Framework includes the international '30x30' target to protect 30% of land and seas by 2030. However, many of the figures for these targets (including 30x30) have limited scientific backing.

Rockström *et al.* (2023) used a series of climatic, water and species conservation models to estimate that 50–60% of Earth would need to remain intact to protect Earth system functions which humanity depend upon. It is likely that the boundary will be on the upper end of this limit as the paper did not consider the uneven distribution of healthy ecosystems, and it is unlikely that intact areas will be optimally distributed. The exact location of the boundary will also depend on the demand for natural services, which in turn depend on the scale and sustainability of human activities, and energy and material consumption. Additionally, thresholds may vary at a biome scale depending on the importance of the biomes' functions; for example, tropical rainforests may have higher thresholds to protect their vital role in climate stability and water recycling.

The limits proposed by Rockström *et al.* (2023) differ slightly from the well-known 'Half Earth' agenda, which has seen significant backlash around its scientific backing, or lack thereof, as well as its potential injustice to many human populations and inability to successfully reach its conservation targets (Büscher *et al.* 2017; Ellis & Mehrabi 2019). Half Earth calls for 50% of Earth to be fully protected, with no human activity or impact. Conversely, Rockström e*t al.* based their limit on 'largely intact natural ecosystems' and do not exclude areas that are not currently under conservation management or areas with human occupation and (sustainable) activity and use. Pimm *et al.* (2018) highlight the importance of prioritising areas that are most biodiverse when nations strive to meet percentage area targets. In their paper, Pimm *et al.* show that if this is not prioritised, it is likely that protected areas – or largely intact natural ecosystems – will predominantly be in biodiverse-poor regions, and thus will not meet conservation goals.

3.2.2. Biodiversity loss: conclusions and recommendations

Most of the studies and proposed limits discussed here highlight the fact that limits on biodiversity loss are based on limited knowledge on biosphere dynamics and responses at the global scale, resulting in limits with high levels of uncertainty. Thus, limits to biodiversity loss should be considered alongside developing and emerging evidence in a way that allows them to be updated as new data become available. There is not yet a consensus on the best metrics to use, owing in part to the broad term 'biodiversity' and the multiple levels at which this can be considered. It is widely agreed, however, that any limits should be two tiered, focusing both on maintaining variation for adaptability and resilience, and maintaining ecosystem functioning.

It is unclear whether global tipping points for biodiversity exist – thresholds which, if crossed, will result large, significant and irreversible change to ecosystems across the globe. Hughes *et al.* (2013) suggest that, due to the interconnectedness of ecosystems as a result of human activities, local state changes could scale up into global state change. Barnosky *et al.* (2012) also support the argument that global systems likely do experience tipping points in the same way as local ecosystems and suggest that a slow build-up of human activities could result in such changes. As evidence for this, the authors point towards the most recent and rapid state shift – the last glacial–interglacial transition – which resulted in new communities within 1,600 years. This was caused by global forcing similar to those experienced today, but at lower magnitudes, suggesting that Earth could experience another state change due to human impacts. The exact point where thresholds lie depends on complex interaction of many factors, which may change based on different biomes and scales.

However, these shifts occur over long time scales. Some studies suggest that there are unlikely to be true tipping points with non-linear, global-scale responses, but that at this scale, there is more likely to be a smooth response pattern, due to spatial and temporal heterogeneity in the drivers and responses to change (Brook *et al.* 2013). Thus, it may not be possible to define a global limit related to critical points and thresholds, indeed thresholds such as 10 E/MSY, as defined in the Planetary Boundaries framework, are related more to value judgements about acceptable levels of loss and associated risks, with different actors inevitably making different judgements about this. Indeed, Hillebrand *et al.* (2023) point out that setting any such limit may be actively harmful, warning that limits may lead to the notion that allowing some level of biodiversity loss is non-consequential, provided that it is below the critical value. The authors highlight that the functioning of ecosystems relies on the complete "entangled web of species interactions," and thus any loss of biodiversity will have negative effects, which are irreversible once the phylogenetic branch is lost (Faith 2015).

Those considering setting targets related to biodiversity loss should note that:

- Defining global limits for biodiversity loss is complex, with many components and ways of measuring limits. There is not yet a consensus on what measures best encompass these roles at a global scale. There are also limits to the data and taxonomic coverage available, which may constrain which measures are feasible regardless of consensus on what is best.
- Many proposed limits are based on value judgement of scientists, giving them a high degree of uncertainty. However, many of the proposed limits set out in this section have had some degree of acceptance from the wider academic community.
- Any global limits need to emphasise the two main roles of maintaining biodiversity:
    1) maintaining genetic diversity to allow the continuation of evolution with changing environments and the persistence of species and ecosystem functions, and
    2) the role of biodiversity in delivering these functions.
- Global limits to extinction rates have been well accepted by the wider academic community and have benefits in being communicable to the public but may be an oversimplification and miss intricacies. The most agreed upon limit that currently exists is to limit global extinctions to 10 E/MSY (extinction per million species per year), with a ten-fold confidence interval (10–100 E/MSY).

- Limits could perhaps focus on measuring species which are “extinction prone” and “functionally extinct,” or focus on taxonomic, phylogenetic and functional diversity to capture the variety of functional traits that are needed to maintain adaptability.
- The Biodiversity Intactness Index (BII) shows some good evidence of correlating with biodiversity loss and has advantages in that it has a high resolution that reduces biases seen in other measurements such as extinction rates. However, there is still a lack of evidence on which this boundary is based on, being defined instead by judgements of a small set of scientists. The limit proposed by Steffen *et al.* (2015) suggests that BII should be kept at 90% or higher, with a large area of uncertainty of 90–30%. These limits do not, however, directly link to biogeochemical and energy flows.
- A limit on HANPP (Human Appropriation of Net Primary Production) of 10% of the stable Holocene levels has been proposed. HANPP has support from a number of academics as a potential limit acting as a proxy for biodiversity loss, even if it is strictly more of a measure of energy at its root.
- Evidence based on modelling of a number of variables suggest that an alternative limit is to keep 50–60% of Earth as largely intact natural ecosystems. This land should be prioritised, for example to cover the most biodiverse areas and areas with rare and vulnerable species. The exact location of the boundary will depend on the demand for natural services and the distribution of intact areas and may differ between biomes.
- Marine biodiversity is often poorly represented in limits and metrics of biodiversity loss and responds to pressures differently.
- Extinction is a non-reversible impact, and it is therefore not possible to introduce policy measures to reverse an extinction event or get back to a level below any extinction ‘limit’ once such a limit has been exceeded.
- It is important to be careful in communication of biodiversity limits to avoid the potentially counterproductive implication that there is a level of human-induced biodiversity loss that is not harmful.

There remains some debate on how Earth will react to biodiversity loss at a global scale and whether true critical limits and tipping points exist for biodiversity loss. More work is required in this field to gain a better understanding of how we can expect Earth systems to respond and how most appropriately to integrate such limits into policy making.

3.3. Biogeochemical flows

‘Biogeochemical flows’ refers to the transformation of elements between different components of the Earth System through biotic and abiotic processes. Anthropogenic changes to biogeochemical flows, which impact processes such as nutrient cycling, cause fundamental changes to ecological and Earth systems. Limits to biogeochemical flows can be related to changes in any element ratio or nutrient cycling (though carbon cycling is usually considered separately in the context of climate change). In most cases, work surrounding biogeochemical flows focuses on phosphorus (P) and nitrogen (N), as these cycles have been drastically altered by human activity through industry and agriculture for consumption, with significant effects on ecological and Earth systems. A key way that humans are altering N and P cycles is through fertiliser application to meet growing demands for crop production and the use, since the green revolution, of crop varieties that require high levels of N (Carpenter & Bennett 2011; Schulte-Uebbing *et al.* 2022; Zhang *et al*. 2015). Loss of these nutrients through direct runoff and soil erosion causes large quantities of P and N to enter fresh waterways and, in turn, oceans (with an estimated 35% of agricultural application eventually entering the oceans; Billen *et al*. 2013), resulting in eutrophication. Eutrophication can cause toxic cyanobacteria algal blooms resulting in anoxic systems, which are unable to support aquatic ecosystems or be used as safe drinking water for humans or livestock (Smith *et al*. 2006).

Nutrient cycles are heterogenous at the global scale, meaning that, although many areas experience eutrophication, many others experience P and N deficiency, making them unsuitable for agricultural activities. This makes the application of a global limit harder to define and implement (Rockström *et al.* 2009). Further, it is not appropriate to set N and P limits to Holocene levels, as done with other limits, as this neglects the need for added inputs to support crop production sufficient to feed current population and modern consumption levels. It is therefore important to take into account the required input of nutrients to maintain healthy diets across the globe when creating these limits. A simple way to think about global biogeochemical flow limits is that anthropogenic manipulation of nutrient cycling should only be constrained by limits in areas where it currently exceeds them.

Healthy and functional ecosystems are essential for maintaining appropriate N and P cycles and flows, so it is important to consider this section alongside discussions raised in the previous section.

3.3.1. Proposed limits to biogeochemical flows, and discussion

In its biogeochemical flows boundary, the Planetary Boundaries framework considers just N and P as nutrients which are vital for biological life, but which have also been significantly altered by anthropogenic activities. In the original PB framework, Rockström *et al.* (2009) defined a single global limit for anthropogenic interference with the P cycle in order to prevent a large-scale ocean acidification event (OAE). In their paper, Rockström *et al*. used Handoh & Lenton's (2003) model to investigate the effect of raising P levels in the deep oceans and predicted that a sustained 10-fold increase in P flow from natural, pre-agricultural states would be sufficient to raise significantly the deep-sea anoxic fraction, potentially resulting in an OAE, where global oceans have similar levels of oxygen depletions as during historic events that resulted in mass marine extinctions. A low estimate of pre-industrial P input was assumed to be 1.1 Tg P yr^{-1}, making the proposed global limit 11 Tg P yr^{-1}. The authors highlight that there are very high levels of uncertainty in these calculations, due to complex interactions between oxic and anoxic states, different P forms, and biotic and abiotic interactions with the P cycle; thus, they attached a 10-fold degree of uncertainty to this estimate (~10–100 times greater than the background rate of P flux). They also noted that the suggested threshold should be treated with caution. Yet, this has proved useful as a target to steer away from, and has been used in a number of reports (e.g. WWF discussion paper – Walking lightly on the Earth 2023).

In lieu of a lack of boundary for freshwater eutrophication, Steffen *et al.* (2015) updated the Planetary Boundary to be two-tiered, containing both a local and global limit. The new boundary contains limits proposed by Carpenter and Bennett (2011) to prevent freshwater eutrophication, as well as retaining Rockström *et al.* (2009)'s 11 Tg P yr^{-1} boundary to limit large-scale OAEs. It was suggested that the flow of P from fertiliser into erodible soils should be limited to 6.2 Tg yr^{-1} (Carpenter & Bennett 2011). To arrive at this proposed limit, Carpenter and Bennett calculated the rate of transport of P from land to freshwater and the rate of P sedimentation, to understand the processes by which fresh waterways become eutrophic. This was then used to estimate target P fluxes that would result in P concentrations capable of maintaining freshwater systems of adequate water quality, thus preventing eutrophication. The authors also noted the interplay between this boundary and that of freshwater flow: higher water flows increase the limit of biogeochemical boundaries, making this boundary sensitive to human-caused changes to the climate and freshwater cycles. However, this boundary still lacks the spatial resolution and detail to account for the heterogeneity in P cycles, in terms of variations in the levels of P, rates of erosion, and in how systems respond to elevated P levels. These calculations also fail to account for some important sources of P, such as human and livestock waste, likely over-estimating the limit. Thus, these calculations are simplifications and likely miss many of the nuances that occur at a regional scale.

Springmann *et al.* (2018) modelled P limits taking into account other sources of P, such as inputs from human and livestock waste, and P accumulation in soils to a critical point where it affects water quality. Neglecting to consider these inputs, as in the work by Carpenter and Bennett (2011), who assumed that soil erosion is the main source of water pollution, may result in over-estimates of boundaries. Additionally, previous models fail to account for increases in P use efficiency (PUE), which may increase the boundary. Springmann *et al*. therefore propose a model that can calculate a threshold of P that prevents eutrophication by taking into account P uptake by humans, waste P from humans, the ability for sediment to store this to a critical threshold, and the ability for soils to accumulate recycled P to a critical threshold. The authors thus suggested a critical threshold of 6–12 Tg P yr^{-1}, which overlaps with Carpenter and Bennet's estimate of 6.2 Tg P yr^{-1}. However, when they assumed a 50% waste recycling rate, as exists currently, the threshold increased to 8–16 Tg P yr^{-1}.

Zou *et al.* (2022) carried out their own estimations based on Springmann *et al.* (2018)'s model and improved PUE predictions. Their model suggests a limit of 4.5–9 Tg P yr^{-1}, which also broadly aligns with estimates cited above.

The planetary boundaries also set proposed limits for N fluxes. Steffen *et al.* (2015) updated the planetary boundaries to include a limit of surface runoff of N, derived by de Vries *et al.* (2013), which aims to prevent freshwater eutrophication and acidification, whilst accounting for the N that is required to ensure that the global population can consume the recommended N intake (noting that human needs can be achieved within Planetary Boundaries; O'Neill *et al*. 2018). de Vries *et al.* identified critical limits for a range of N indicators from the literature and used these to perform back calculations to estimate N boundaries. To prevent freshwater eutrophication and acidification, the N concentration in surface waters should be kept below 1.0–2.5 mg N l^{-1} (Camargo & Alonso 2006; Laane 2005; Liu *et al.* 2012). Taking the lower limit of 1.0 mg N l^{-1} dissolved inorganic N, the authors were able to back calculate critical N losses and, in turn, critical values of N that can be fixed to remain within this limit. Their calculations also considered crop's nitrogen use efficiency (NUE), and N loss to account for the amount of N fixation that agriculture requires to ensure crops can be grown that meet global demands of recommended N consumption. This method resulted in a global limit of 62 Tg N yr^{-1}, which was included into the planetary boundaries update. Taking the upper limit of 2.5 mg N l^{-1} results in a boundary of 82 Tg N yr^{-1}.

As there is so much spatial variability in anthropogenic N use, with heavy application in areas of intensive agriculture, and depletions in areas unsuitable for crop growth, this global limit is not suitable for all locations. Instead, de Vries *et al.* (2013) suggest using it to limit N fixation in agricultural areas which are currently being exceeded. A limitation of this approach is that it considers only N that is used in agriculture, and negates its effect from non-intentionally fixed sources, such as animal manure, industry and wastewater. Therefore, the boundaries proposed may be too high.

Schulte-Uebbing *et al.* (2022) tried to account for spatial heterogeneity in both N losses and in regional sensitivities to N, by using a spatially explicit model to produce local boundaries of surplus agricultural N losses. Using measures of surplus N can be considered a more robust indicator, as it does not require assumptions of NUE when calculating the amount of N required by crops, which can differ substantially by crop, region and time. Aggregating these local boundaries produces a global limit for individual N indicators, as well as a global limit when considering all indicators alongside each other. When producing a limit to prevent eutrophication, as with other boundaries discussed here, the aggregated model suggests a planetary boundary of 69 Tg N yr^{-1}, which fits within de Vries *et al.*'s estimate of 62–82 Tg N yr^{-1}. However, the authors estimate that if areas that do not currently exceed the threshold are enabled to increase their N application in order to meet agricultural demands, this threshold can be increased to 92 Tg N yr^{-1}, raising the limit by 33%.

Steffen *et al.* (2015) suggest that estimates of N and P boundaries can be verified based on the N:P ratio of crop plants. As fertiliser application is a leading cause for anthropogenic disturbance to both the N and P cycles, Steffen *et al*. applied Greenwood *et al*. (2008)'s N:P ratio in growing crop tissues of 11.8 to 1 to determine a boundary of one nutrient if the other can be estimated. Using the P boundary of 6.2 Tg yr^{-1} (Carpenter & Bennett 2011) and multiplying this by the N:P ratio gives an N boundary of 73.16 Tg yr^{-1}, which again falls within the range estimated by de Vries *et al.* (2013). Conversely, using de Vries *et al.* (2013)'s lower estimate of 62 Tg N yr^{-1} and dividing this by 11.8 produces an estimated P boundary of 5.25 Tg yr^{-1}, which aligns with Zou *et al.* (2022)'s and others estimates. These figures, derived from independent methods, are similar to each other and are likely to be within the confidence intervals of error, suggesting agreement and consistency.

3.3.2. Biogeochemical flows: conclusions and recommendations

Most of the studies identified here are based on modelling numerous complex interactions that are not fully understood. Therefore, the estimated boundaries are associated with a high degree of uncertainty and should be updated as interactions become better understood and as new data become available. For the impacts of both nutrient cycles on freshwater systems, there is a high degree of spatial heterogeneity, both in the levels of these nutrients and in the ways that the system responds to increased input. To meet these limits, areas should only reduce their impact when they are currently crossing the thresholds. There is some evidence that if areas that are not currently crossing the thresholds intensify their nutrient use, these global thresholds can be increased. Most studies focus on defining boundaries to prevent eutrophication. However, there are other impacts of altering biogeochemical flows (for example, elevated nutrient levels in groundwater), and some work suggests that to reduce all associated impacts, one must adhere to limits which are stricter, highlighting a possibility of widespread over-estimates in boundary setting.

Those considering setting targets related to P and N biogeochemical flows should note that:

- There are limits to how low these boundaries can be set whilst also sustaining a healthy, nourished population. The amount of N and P that is required for food production is likely to change as NUE and PUE increase, populations increase, and diets and the distribution of food improve.
- A global P input of around 11 Tg P yr^{-1} has been proposed to prevent eutrophication of oceans. However, this is based on limited research and has a high degree of uncertainty.
- A local P input in the region of 4.5–16 Tg P yr^{-1} has been proposed to prevent freshwater eutrophication, depending on model inputs and assumptions, but with a large consensus around the 6 Tg P yr^{-1} mark.
- A global N boundary of 62–82 Tg N yr^{-1} is considered to limit impacts of eutrophication. This limit increases to 92 Tg N yr^{-1} if areas that are not reaching this limit are able to intensify their nutrient use.
- Most thresholds concentrate on the effect of eutrophication. Some research suggests that these limits need to be reduced when considering all effects of altering biogeochemical flows.
- Spatial heterogeneity means that these boundaries should only result in limitations on N and P use in areas where the limits are already crossed.

- Many studies do not cover all sources of N and P and have high levels of uncertainty due to complex interactions and spatial heterogeneity.

3.4. Material footprint

Material Footprint is a measure of material extraction (usually including minerals, fossil fuels, and biomass) associated with consumption of goods and services (O'Neill *et al*. 2018, Supplementary Information). It can successfully capture complexities in human production and consumption patterns. For example, Material Footprint can account for consumption of imported materials (and therefore offshored impacts), as well as those extracted domestically, raw materials embedded in other products, and unused material extraction (i.e. materials that are extracted but not used in the human economy, such as fishing bycatch, though not all Material Footprint calculations include unused material extraction). Material Footprint is often seen to act as a proxy of multiple environmental pressures resulting from resource flows which are not comprehensively measured by single impact metrics (e.g. those focused solely on nitrogen flows, or biodiversity loss) (Bringezu 2015), and these multiple pressures can be reduced together if Material Footprint is reduced. However, Material Footprint does not directly measure specific environmental impacts of production and does not indicate changes in the ability of nature to provide ecosystem services. Different materials have very different environmental impacts, so it would be quite possible for the overall aggregate material footprint to decrease, while important environmental impacts increased.

Material Footprint is therefore a measure of the *amount* of consumption, but not of consumption *impacts,* and so does not give a complete picture of the sustainability of consumption. Understanding and measuring the 'amount' of consumption can inform action around increasing the circularity and efficiency of economies (e.g. through reducing waste), and meeting targets to reduce Material Footprint will likely reduce overall impacts of consumption. Further, Material Footprints can be 'environmentally extended' – directly linked to environmental impact metrics. For example, the Global Environmental Impacts of Consumption Indicator first estimates Material Footprint associated with consumption of particular commodities, and then estimates several environmental impacts (such as deforestation, water use) associated with producing the estimated amount of the commodity consumed (SEI/JNCC 2023). Using Material Footprint as a step in the process to estimating environmental impacts in this way explicitly links these impacts to specific consumption patterns (e.g. of a particular commodity, or by a particular economy), rather than consumption by the planet, which can make target-setting more specific and meaningful.

Material Footprint can be broken down into different components, such as biomass footprint or non-metallic ores, and it may be appropriate to set targets against each of these separately. However, in the context of this report, we focus on the overarching Material Footprint.

3.4.1. Proposed limits to Material Footprint, and discussion

Several sources suggest that the threshold for a sustainable per capita Material Footprint is around 6–8 tonnes per year (Lettenmeier 2018; Lettenmeier *et al*. 2014; O'Neill *et al*. 2018; UNEP 2011). These sources informed the Draft Circular Economy Strategy for Northern Ireland, a consultation on which closed in March 2023, which included a target to reduce Material Footprint from the current estimated 16.6 tonnes to 8 tonnes per person per year by 2050 (Department for the Economy 2022).

One of these sources, O'Neill *et al*. (2018), looked at various proposed Material Footprint thresholds, selected a commonly cited global target of 50 billion tonnes per year, and divided this by 7 billion (an assumed world population) to come up with a per capita material threshold of 7.2 tonnes per year (see the paper's Supplementary Information for their methods and sources). However, given that the global population currently exceeds 7 billion, this per capita threshold is currently too high according to this approach. Following O'Neill *et al*. (2018)'s method, global material consumption of 50 billion tonnes per year would be met by an average per capita consumption of 6.3 tonnes per year given the current estimated population of 8 billion, and of 5.2 tonnes per year given the projected population of 9.7 billion in 2050 (population estimates from United Nations, Department of Economic and Social Affairs, Population Division 2022). This has led to increasing calls from European environmental NGOs to adjust this limit based on population (Meysner *et al*. 2024; Sufficiency Coalition and Resource Use Reduction Taskforce 2024).

Further, the global target of 50 billion tonnes per year appears to have been selected arbitrarily. A common source of this figure is a report by Dittrich *et al.* (2012) in which the authors suggested that Material Footprint should be frozen at the level of a base year; 50 billion tonnes is used as this was the global footprint in 1992, the year of the first Rio Summit, rather than being based on any mechanistic understanding of thresholds and tipping points.

UNEP (2011) suggest a Material Footprint limit of between 6 and 8 tonnes per person per year based on scenario modelling (with the upper and lower bounds of this range resulting from two different scenarios). The limit suggested aims to meet the needs of the global (consuming) population, with some reduction of material consumption. The scenarios are based on assumptions, including future convergence whereby all countries will have similar levels of resource use by 2050 at the latest (while currently, people living in developed countries have far higher average Material Footprints than those living in developing countries). The only scenario related to a particular environmental threshold proposes a limit of 6 tonnes per person, which was calculated as the requirement to stay within the IPCC's at the time recommended limit of 2°C warming above pre-industrial levels. This is also the only scenario which does not raise global resource consumption above the baseline year (2000) level; the authors write "thus it would be most compatible with the [at the time] existing (if unknown) limits to the Earth's resource base, and best adjusted for as much circularity in economies as is technically feasible." However, the authors note that this scenario would require unprecedented innovation underpinning radical technological and system change. In this scenario, even some countries classed as 'developing' in 2000 would have to reduce average Material Footprint, while eliminating poverty. Further, all the scenarios assumed a 2050 population of 9 billion, whereas more recent estimates project a global population of 9.7 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division 2022). Therefore, the limit of 6–8 tonnes per person per year limit would be reduced if re-scaled based on the latest population projections, and on the IPCC's current recommended limit of 1.5°C warming above pre-industrial levels. The fact that Material Footprint does not have a direct link to GHG emissions (different components of the footprint are linked to different levels of GHG emissions) adds further uncertainty to this conclusion.

Lettenmeier *et al*. 2014; 2018) proposes a 'household' Material Footprint for Finland (including all aspects of consumption that households can directly influence) of 8 tonnes per person per year by 2050, with sustainable public consumption (including, for example, health care, education, water supply and waste-water treatment) proposed as 2 tonnes per person per year. The sustainable Material Footprint is based on the 10 tonne per person per year level for the total material consumption for European countries proposed by Bringezu (2009; note that the full reference could not be accessed), and assumes that 80% of this is assigned to household consumption, and the remaining 20% to public consumption. Lettenmeier *et al*.'s calculations take into account abiotic and biotic material resources (including their unused extraction) and erosion in agriculture and forestry associated with entire life cycles (from extraction to final waste disposal) of products and services consumed.

Several assumptions are made, for example that future resource intensities of materials, products and activities will be lower than they are now – based on plausible resource efficient potentials identified in other studies. The study breaks down current 'status quo' and suggested sustainable Material Footprints for different components of household consumption (Table 1), prioritising more basic needs (e.g. nutrition) over other activities such as leisure for the suggested sustainable footprint. The authors identify pathways for achieving these limits, for example the sustainable footprint for nutrition is based on consumption of largely vegetarian diets, a slightly reduced amount of foodstuffs consumed compared to today, and food chain efficiency gains (e.g. reducing waste).

Table 1. Summary of status quo annual Material Footprints in Finland and proposal for sustainable annual Material Footprint requirements across different consumption components, from Lettenmeier *et al*. (2014).

Consumption component	Status quo Material Footprint		Sustainable Material Footprint		Change required	
	kg/ person	Share	kg/ person	Share	%	Factor
Nutrition	5,900	15%	3,000	38%	-49%	2.0
Housing	10,800	27%	1,600	20%	-85%	6.8
Household goods	3,000	7%	500	6%	-83%	6.0
Mobility	17,300	43%	2,000	25%	-88%	8.7
Leisure activities	2,000	5%	500	6%	-75%	4.0
Other purposes	1,400	3%	400	5%	-71%	3.5
Total	**40,400**	**100%**	**8,000**	**100%**	**-80%**	**5.0**

3.4.2. Material Footprint: conclusions and recommendations

The estimates described in this section are based on prior research, assumptions, and, to some extent, value judgements. For example, the work by Lettenmeier and colleagues is based on calculations by Bringezu which is in turn based on the assertion, and associated calculations, by Schmidt-Bleek (1993; full reference could not be accessed) that global resource consumption should be halved by 2050 and equal per capita use should be achieved, as well as estimates of ecological carrying capacity and other measures. Due to the inherent complexities, Lettenmeier (2018) writes, "there is still no major new breakthrough in determining in detail a sustainable level of abiotic resource use." Despite these challenges, several attempts incorporating different inputs and methods of calculations have converged at similar thresholds for Material Footprint (around 6–8 tonnes per person per year). However, it is important to note that any such threshold and pathways for staying within a limit may need to be updated in light of more up-to-date information such as new population estimates, and technological improvements (which may occur at a slower or faster rate than currently assumed); as well as considering substitutability between different commodities within the footprint that may have different levels of environmental impact.

Those considering setting targets related to the Material Footprint should note that:

- Any target set aiming to reduce Material Footprint is likely to reduce the impacts associated with consumption.

- 6–8 tonnes per person per year is relatively well accepted in the literature as a sensible 'limit'; however, this is largely based on value judgements or returning to ‘baseline’ years, rather than any scientific understanding of thresholds and tipping points.
- The 6–8 tonne limit is based on assumptions (e.g. related to population growth) and should be updated in line with new information as it becomes available. This limit may be too high given current population estimates, and the recommendation from the IPCC that warming should be limited to 1.5°C above pre-industrial levels.

Where data are available, targets related to reducing specific impacts are likely to be more meaningful than targets related to Material Footprint. Linking impact-based targets with Material Footprint targets may be an effective way of directing action around consumption and production patterns linked to specific impacts.

3.5. Ecological Footprint

The Ecological Footprint is an estimate of how much regeneration (bioproductive land and water area) would be required to produce natural resources that are consumed and to sequester carbon dioxide that is produced. This is in recognition that planetary resources are finite. If we are consuming more than can be regenerated, this is not sustainable. Results are presented as the total area required to support resource consumption (cropland, grazing land, fishing grounds, built up land and forestry) and to absorb carbon dioxide emitted (e.g. sequestration through forest planting), normalised by global average productivity to give a unit known as ‘global hectares.’

3.5.1. Proposed limits to Ecological Footprint

The ‘limit’ implicitly designed as part of measures of Ecological Footprint is the comparison between the Ecological Footprint (demand on resources) and biocapacity (ability to regenerate). If Ecological Footprint exceeds biocapacity, this implies an ‘ecological deficit’ or ‘overshoot.’ This analysis can be undertaken at any scale; if the Earth’s Ecological Footprint is larger than one planet, or if a country or city’s Ecological Footprint is larger than the biocapacity of that area, then they have surpassed the limit as defined by the Ecological Footprint concept. At a global scale, this implies a combination of ecosystem degradation, natural capital loss and accumulation of CO_2, whereas at a smaller scale it may mean that demand is being met from outside the system (and therefore footprint is being ‘offshored’ inequitably), for example through trade.

3.5.2. Discussion of proposed limits to Ecological Footprint

The Ecological Footprint has had wide uptake by Governments around the world and in the media but has also received notable criticism in the academic literature (Gordon & Richardson 1998; van den Bergh & Verbruggen 1999; Ayres 2000; van Kooten & Bulte 2000; Grazi *et al*. 2007; Fiala 2008; Blomqvist *et al*. 2013). Many of these criticisms focus on its relevance to sustainability agendas, its strong carbon component, and its lack of ability to take intensification into account.

In terms of its relevance to sustainability agendas, some argue that at a national scale it is a better measure of self-sufficiency than sustainability, so lacks relevance to sustainability-based policy (Jennings *et al*. 2024). Others have compared data on the Ecological Footprint with more direct data on environmental impact such as metrics of land degradation and found little correlation (Fiala 2008).

The fact that, in most cases, the land estimated to be required to sequester carbon released, forms such a substantial proportion of results (often over 50% in middle- and high-income countries, has also been criticised. One study showed very little difference in results of the Ecological Footprint and results from direct measurements of tonnes of carbon emitted (Fiala 2008), leading to concerns that users will interpret changes to the management and area of other land use types as having very little impact, when from an ecological perspective this is not true (Jennings *et al*. 2024). It also assumes that carbon sequestration is only happening through plantation of forests, when in reality it may be done through means requiring less land use, such as peatland restoration and blue carbon (van den Bergh & Grazi 2015). The inclusion of this aspect can lead to a mismatch in what some users intuitively understand when they see results (that we require more than one planet to produce the resources we use) and what the results show (that we would require more than one planet if sequestering all of the carbon we produce, as well as producing the resources that we use).

Limitations relating to the Ecological Footprint's lack of ability to take intensification of production into account and potential for this to lead to perverse incentives have also been flagged. The Ecological Footprint assumes that any increase in production happens extensively (i.e. through use of more land), whereas in reality, intensification of production has supported a lot of recent demand increase globally (Fiala 2008). Intensification of production will lead to the land having a higher apparent 'biocapacity' and ability to support a higher level of consumption without apparent 'overshoot.' However, intensification is often associated with higher levels of land degradation. Therefore, the area of land required to support consumption (normalised by world average productivity), may not alone describe the sustainability of a particular land use: the amount of degradation caused by that land use is important too (Fiala 2008).

In addition, it does not take into account the depletion of non-renewable resources like metals and other minerals, only accounting for them in so far as they require land to extract, or to sequester the CO_2 released in their extraction.

Nonetheless, the Ecological Footprint is a powerful communication tool. Even its critics complement its "commendable job of condensing a complex array of consumption down into a single, intuitive number" (Fiala 2008). It is easy to visualise the units that it communicates, especially when presented as the number of planets, exceeding our own, that are required to support consumption, making it effective at capturing attention and highlighting evidence of the need for action (Harris 2023a).

3.5.3. Ecological Footprint: conclusions and recommendations

Unlike in previous sections, where limits have been proposed against particular environmental impact types of interest, the Ecological Footprint attempts to provide a holistic measure of the balance between resource supply and demand. Both widely adopted and widely criticised, of the options considered in this report it is perhaps the most conceptually simple scientifically defined limit (the space available vs the space required to support consumption and sequester carbon).

Those considering setting targets related to the Ecological Footprint should note that:

- It provides an easy-to-communicate, in-built global limit of one planet resource use, although this can also be seen as oversimplified and is easy to misinterpret its exact meaning for those who do not dig into the detail of the methods behind it.
- Exceeding one planet's worth of resource use at a global scale will lead to some combination of ecosystem degradation, natural capital loss and accumulation of CO_2, although in reality this is usually largely CO_2 accumulation.

- Limits can be downscaled to country or city level (i.e. the limit for the UK's consumption would be the UK's biocapacity), but users should note that at this scale it is often more of a representation of offshoring and self-sufficiency than it is necessarily of impact.
- It should not be interpreted as a direct measure of environmental degradation or ecological change, but rather a theoretical accounting of supply and demand.

4. Challenges and opportunities associated with limits for sustainable consumption

This section discusses some of the challenges around defining limits for sustainable consumption, some recommendations regarding those challenges, and opportunities to apply limits for sustainable consumption.

4.1. Key challenges

4.1.1. Limits are based on assumptions and value judgements as well as science

One of the aims of this review was to understand the scientific basis of proposed frameworks and limits. However, most of the limits that came up in the literature review and that are discussed here are, necessarily, based on a combination of research, assumptions, and value judgements about levels of acceptable risk – which can be difficult to disentangle. For example, limits to Material Footprint are commonly calculated relative to a global target of 50 billion tonnes per year baseline. However, there seems to be no scientific rationale for this target beyond this being the calculated global footprint in 1992 and therefore this is known to not exceed limits to the Earth's resource base in the immediate term. Further, some of the science and assumptions underpinning limits can become outdated, such as global population estimates used to calculate per capita limits. Depending on the quality of the empirical evidence available, this element of judgement about acceptable risk is applied in different ways and may affect the subsequently proposed limit to lesser or greater degrees. For example, as Material Footprint is not a direct measure of impact, the risk judgement is fundamental to setting a limit (e.g. by choosing a perceived 'low risk' baseline year), whereas in cases where the scientific evidence is clearer (such as the probability of widespread ocean anoxia for P pollution), the risk judgement is more tightly linked to scientifically determined thresholds.

Defining and adopting limits also inherently involves ethical judgements. This includes judgements relating to intragenerational justice (between countries, communities and individuals) and intergenerational justice (between current and future generations) on how the benefits and risks of consumption are distributed amongst people. However, approaches to making relevant ethical judgements about how to define upper limits are not always transparent, and often reflect the assumptions of researchers who – in regards to the limits discussed in this paper – are typically based in wealthy industrialised nations (Biermann & Kim 2020). Other approaches consider ethical and social issues more explicitly than the majority of those discussed in this report. For example, social baselines to meet human needs rather than upper limits to consumption alone are incorporated into concepts such as Doughnut Economics (Raworth 2017), Consumption Corridors (Fuchs *et al*. 2021), and Safe and Just Earth System Boundaries (Rockström *et al*. 2023). The Safe and Just Earth System Boundaries framework, which builds on the Planetary Boundaries framework, amongst others, also considers 'interspecies justice.' While limits are often defined in relation to meeting human needs – for example, Planetary Boundaries as the upper limits to a 'safe operating space' for humanity – the interspecies concept recognises that consumption also impacts non-human species.

4.1.2. Global limits are difficult to downscale

A challenge with all global limits is how to downscale them across economies, nations, ecosystems, sectors, and individuals (Dao *et al*. 2018; Ferretto *et al*. 2022). One option is a top-down per capita approach, whereby shares of a global limit are distributed equally based on global population estimates each year (e.g. Lettenmeier 2018; Lettenmeier *et al*. 2014;

O'Neill *et al*. 2018; UNEP 2011). However, this assumes that all citizens should have the same limits to consumption, which invites ethical and practical discussion (O'Neill *et al*. 2018). For example, there is some evidence that densely populated regions require fewer resources per capita for the same standard of living as sparsely populated areas (UNEP 2011). It could therefore be argued that more densely populated areas should aim for a lower Material Footprint, so that a given standard of living is equally distributed, rather than equally distributing a given Material Footprint.

Geographic and environmental variations may also make per capita methods an inappropriate way to manage some environmental impacts of consumption. As discussed above, there are difficulties defining global boundaries for N and P limits in particular, due to the fact that some areas of the world are deficient in these nutrients, so encouraging a reduction across the board is not appropriate. O'Neill *et al*. (2018) give the example of freshwater, which is a geographically and temporally bounded resource, and therefore local river-basin geography and monthly timescales may be more appropriate scales for management. Sub-global environmental variations and thresholds are somewhat addressed in more recent updates of the Planetary Boundaries framework, which defines regional as well as global boundaries (Richardson *et al*. 2023; Steffen *et al*. 2015). Dasgupta (2021) notes the importance of this, as crossing regional level boundaries (e.g. destruction of the Amazon rainforest) can impact the entire Earth system.

4.1.3. Simple limits may mask complexities in the impacts of consumption

While limits that are conceptually simple are more likely to be applied successfully, there are drawbacks associated with simplifying complexities in how production and consumption drive different environmental impacts. For example, many limits focus on specific (often singular) impact types, but many impact types may be connected by their drivers and consequences. Multiple impact types (perhaps multiple limits) must be considered holistically to avoid shifting environmental burdens from one impact type to another, and to account for interactions between impact types (such as between biogeochemical flows and climate change; Lade *et al.* 2020). Further, simple limits may not encompass all the relevant impacts of consumption. For example, Material Footprint is a measure of the *amount* of consumption, but not of consumption *impacts* which are also related to production practices. An approach to resolving this issue in the case of Material Footprint is to directly link calculated footprints to environmental impact metrics (i.e. environmentally extending a Material Footprint (e.g. the GEIC indicator; van der Voet 2008)).

4.1.4. Translating limits into policy presents its own challenges

While scientifically robust limits present an opportunity to direct actions on the harmful impacts of consumption, there remains the challenge of how to translate those limits into policy. The environmental impacts of consumption are wide ranging and mediated at different scales via a number of mechanisms, from international trade to household-level consumption, which interact with economics, lifestyles, culture and values. Reviewing methods to implement limits or integrate them into policy is outside the scope of this review, but a wealth of studies explore opportunities in this area. For example, Lettenmeier *et al*. (2014) present a range of promising examples and practices supporting proposals for each component of a sustainable household footprint, and Lettenmeier's (2018) follow-up research with households in Finland found that it was possible to reduce Material Footprint via relatively few changes in everyday living. In a report commissioned by WWF, Kennedy *et al*. (2020) couple outcome-based targets with action-based targets, which describe specific actions that can be taken to meet the outcome-based targets, with the overall aim of halving the footprint of production and consumption.

4.2. Opportunities and recommendations for applying limits for sustainable consumption

Despite the challenges outlined above, applying limits is important for catalysing action. A simpler alternative to defining limits for sustainable consumption would be to instead aim for reductions in unsustainable consumption (i.e. aiming for directional change rather than staying within defined limits). However, given the scale of the environmental crises humanity currently faces (IPBES 2019; IPCC 2023; One Planet Network 2024), and uncertainties around the risks to people and nature as Earth systems move into new states (Richardson *et al*. 2023; Rockström *et al*. 2009; Steffen *et al*. 2015), directional change without substantial, clearly-defined and broadly-accepted limits is likely to be insufficient. The evidence is clear that setting targets against a well-defined limit increases the likelihood of action towards achieving this target, through psychological motivation (Latham 2004), resource mobilisation (Fukada-Parr 2014) and increased collaboration between different stakeholders (Kleingeld *et al*. 2011). This applies at an individual (Latham 2004), group (Kleingeld *et al*. 2011), and global (Fukada-Parr 2014) scale. Therefore, despite the challenges in defining quantitative limits, they could play an invaluable role in addressing these environmental crises. The science is clear that we are consuming at an unsustainable rate, and so the lack of science's ability to define clear and precise targets for exactly how much should not be used as a reason to avoid setting a target and acting to reduce the impacts from consumption at all.

Below are some recommendations for addressing the challenges identified in this section, to apply limits as usefully as possible:

- Defining limits to consumption, or associated impacts, is a highly complex task and inherently based on ethical judgements. Therefore, a dependence on previous research and (sometimes subjective) assumptions is inevitable. When considering and applying different limits, it is important to recognise where assumptions and value judgements may introduce uncertainty to the proposed limits or make it appropriate to update them in line with new evidence.
- Downscaling limits appropriately is a challenge, especially given the many complexities and interactions around the environmental and social dimensions of downscaling (Usubiaga-Liaño & Ekins 2021). For example, appropriate fertiliser use at a regional scale may depend on agricultural production methods, crop type, soil types, and trade, as well as consideration of the global limit. When downscaling limits, social and environmental context should be carefully considered. Applying complementary approaches, rather than reliance on single frameworks or limits, may be appropriate.
- Limits that are conceptually simple mask complexities in consumption and production impacts, which are associated with risks such as shifting environmental burdens from one impact type to another, or missing key impacts associated with consumption and production. It is important to consider impact types holistically and, where appropriate, use complementary approaches to define limits and direct action (Usubiaga-Liaño & Ekins 2021).
- Moving from scientifically robust limits to policy and action poses its own challenges, which have not been assessed in this review. There is a rich literature on approaches to implementation of different limit types. A previous JNCC report (Harris 2023b), explores actions that can be undertaken by governments to encourage sustainable consumption in greater detail.

5. Conclusions

Whilst there are many well-accepted limits for sustainable consumption linking human impacts on the environment to thresholds which, if surpassed, are likely to result in harmful impacts for people, these vary in the extent to which they are based on evidence vs subjective factors. All frameworks and limits involve assumptions and value judgements, so policymakers wishing to define limits and set targets in relation to the sustainability of consumption must consider the evidence alongside their own risk appetite and political ambition and ensure that they are aware of any assumptions behind evidence used. That said, given the need for widespread action across diverse stakeholders, aligning with widely accepted limits, such as those summarised within this report, is likely to be an effective starting point to bring actors together towards a common goal and create the directional change that is needed. Global limits should be applied taking into account current social and environmental contexts and updated over time in light of new information. No single framework or limit comprehensively encompasses all environmental impacts of consumption, and so it is likely that a suite of different and complementary limits will be required to avoid negative trade-offs and most effectively direct action. Social impacts of consumption (including social baselines to meet human needs) are also important to consider.

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Weblinks

Table 2. Full URLS for weblinks used in the text.

Weblink text	Full URL
Ecological Footprint	https://www.footprintnetwork.org/our-work/ecological-footprint/
Environmental Improvement Plan	https://www.gov.uk/government/publications/environmental-improvement-plan
Glasgow Leaders' Declaration on Forests and Land Use	https:/ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/
Global Environmental Impacts of Consumption (GEIC) indicator	http://www.commodityfootprints.earth/
Kunming-Montreal Global Biodiversity Framework (GBF) Target 16	https://www.cbd.int/gbf/targets/16
Northern Ireland's Sustainable Development Strategy	https://www.daera-ni.gov.uk/publications/ni-executive-sustainable-development-strategy-everyones-involved
Science Based Targets Network	https://sciencebasedtargetsnetwork.org/
Scotland's Environment Strategy	https://www.gov.scot/publications/environment-strategy-scotland-vision-outcomes/documents/
Special Report on the impacts of temperature increases of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways	https://www.ipcc.ch/sr15/
Sustainable Development Goal (SDG) 12	https://sdgs.un.org/goals/goal12
Wellbeing of Future Generations Act	https://www.futuregenerations.wales/about-us/future-generations-act/
WWF discussion paper – Walking lightly on the Earth	https://wwfint.awsassets.panda.org/downloads/wwf-discussion-paper_walk-lightly-on-earth_footprint-of-oecd-countries_october-2023-final.pdf
2015 Paris Agreement	https://www.un.org/en/climatechange/paris-agreement
2030 Strategic framework for international climate and nature action	https://www.gov.uk/government/publications/2030-strategic-framework-for-international-climate-and-nature-action
25 Year Environment Plan	https://www.gov.uk/government/publications/25-year-environment-plan

Appendix 1: Could limits be set against the metrics included within the GEIC indicator?

Introduction

Much of JNCC's previous work on sustainable consumption has focused on measuring the impacts of consumption. This has included, alongside partners at SEI York, the development of the GEIC indicator (available at www.commodityfootprints.earth), which estimates the deforestation, biodiversity loss, water use, and a range of other environmental impacts associated with consumption across 141 countries/territories of the world. This is estimated through combining economic modelling with country- and commodity-specific environmental data. It is one of the few tools available that links consumer nations to their impacts overseas with the granularity to see the producer countries and commodities behind results. It does not set limits against any of these impact types; it simply measures their extent. This Appendix explores whether it would be appropriate and scientifically valid to explicitly include a 'limit' or threshold in the presentation of the data for each metric, to aid in interpretation.

Deforestation, and associated GHG emissions

Many countries (and companies) are making zero-deforestation commitments, in response to increasing understanding of the carbon, biodiversity and livelihoods-based benefits that forests provide. For example, the Glasgow Leaders' Declaration on Forests and Land Use is a commitment by 140 countries, accounting for more than 90% of Earth's remaining forests, to halt and reverse forest loss and land degradation by 2030. Similarly, both the European Union and the United Kingdom are implementing policies that will obligate companies above a certain size to perform Due Diligence on their supply chains for certain high-risk commodities, to ensure that imports have not led to deforestation (EU) or illegal deforestation (UK) where produced. The Planetary Boundaries' 'land system change' boundary, which is based on forest area, has also been surpassed. It therefore seems widely accepted that the limit for deforestation has already been passed. Whilst, as with the cases described in the main report, this is not based on any kind of scientifically defined 'tipping point,' it does represent a broad political consensus.

GHG emissions have a well-accepted global limit of 1.5°C. The IPCC have translated this to a need for net zero CO_2 emissions by 2050. Given this, alongside the general agreement on a need for zero deforestation, it would seem that 'zero' would be the obvious limit to aim for from a GHG emissions from deforestation perspective as well.

If implementing a zero-deforestation limit against the GEIC indicator's deforestation metric (and associated GHG emissions metric), consideration would need to be made of a key assumption behind the model. The model assumes that impacts related to a particular commodity within a source country are proportionally distributed to the countries consuming that commodity from that country. This assumption means that the deforestation value can only reach zero if no deforestation were taking place at all in any of the countries being sourced from related to the commodity(ies) of interest. For example, if 100 hectares (ha) of deforestation were taking place in country A to produce a given commodity, and 60% of the commodity was being consumed domestically in country A, while 40% was exported and eventually consumed in country B, then the model would associate 60 ha of deforestation with country A, and 40 ha with country B. However, it is possible that country B is sourcing the commodity only from areas outside of this 100 ha, and that the 100 ha of deforestation is caused directly by the 60% of the commodity being consumed domestically. As the model is not spatially explicit enough to identify this, it would still attribute those 40 ha of deforestation to country B. This is not necessarily wrong (country B may not be consuming a commodity that comes directly from deforested land, but it is still contributing to demand that is leading to that 100 ha of deforestation), but is an issue that could cause confusion if attempting to implement a zero deforestation limit against the indicator. This assumption and its associated uncertainty would need to be considered in other cases as well but may be most apparent if aiming for zero and unable to reach zero due to external factors. Despite this challenge, it is worth noting that the GEIC model does have good commodity specificity and so the impact of this assumption on model outputs is reduced compared to many similar approaches.

Another challenge related to zero-deforestation limits is that they may lead to displacement of land use change impacts into other equally valuable habitat types, such as grassland and wetland. Setting a limit against GEIC would currently be unable to account for this; although potential future work may expand the scope of habitats covered.

As GEIC does not measure reforestation, it would not be relevant for assessing recovery towards any kind of limit that may have already been surpassed, but reforestation data could be considered alongside it to calculate a net result.

Biodiversity loss

The GEIC indicator provides three separate metrics of biodiversity loss. The LIFE score estimates extinction risk from habitat change associated with crop-commodity production. The limit of 10 extinctions per million species per year proposed by Rockström *et al*. (2009) – and discussed in Section 3.2.1 of this report – could therefore be applied here, downscaled to country level by, for example, dividing this total per capita. For example, the GEIC indicator's LIFE score estimates that the UK's consumption in 2022 was associated with committing 4 species (of the ~ 30,000 species in scope) to extinction within the next 100 years. In a rough calculation, this equates to 1.33 extinctions per million species per year. The UK's population in 2022 was 0.8% of the world's total, meaning this exceeded the national limit of 0.08 extinctions per million species (0.8% of 10 per million species) by a factor of about 16.7. As the LIFE score is primarily a land conversion-based metric, it does not capture all stressors on biodiversity (such as pollution), and so it should also be noted that this is likely an underestimate. Further, as noted previously, this proposed limit is not based solely on scientific evidence but rather incorporates value judgements and assumptions related to maintaining Holocene-like conditions. It therefore may not be appropriate to incorporate such limits into an otherwise neutral and impartial evidence source such as GEIC or, at the very least, these value judgements and assumptions must be clearly communicated alongside GEIC's scientific outputs.

In contrast, the species richness-weighted crop area metric (which estimates the hectares of crop production scaled by the number of species present in that hectare, therefore showing where there is overlap between production and areas of biodiversity importance), does not relate well to any limits proposed in Section 3 and may pose a greater challenge to define a limit against. Similarly, the predicted species loss metric refers to regional extinction rates and so is not directly comparable to the Rockström limit.

Water

Water has some complex nuances to consider when setting limits. The amount of water required to support different ecosystems and different crop types varies significantly, as does the amount of water available, so setting a global limit is unlikely to be meaningful. The current approach of the indicator, reporting on both water use and scarcity-weighted water use, goes some way towards showing both the result and the result within a limit-relevant context (the remaining water available per watershed, after the demand of human and aquatic ecosystems has been met). This way, the limit is set at the point of production, rather than consumption, so water availability and the differences in water used per crop can be considered. However, it does not go as far as identifying the amount of water remaining that is considered 'too little.' This could be considered in a similar way to metrics considered above, where the evidence and data can provide parameters within which it would be possible to take a value judgement related to risk, but which does not implicitly include a science-based limit itself.

Biomass

The GEIC indicator also provides an estimate of the tonnes of agricultural commodity production embedded in consumption. Whilst the Material Footprint limits discussed in Section 3.4 cover all material use (e.g. metals/minerals, marine commodities, plastics), the GEIC indicator only covers biomass from agricultural crop commodities, cattle, and timber. Whilst various approaches have been suggested for defining a limit related to biomass specifically (including basing it on a proportion of a Material Footprint limit, or on HANPP as discussed in Section 3.2.1), none of these have gained consensus or become widely accepted (Jennings, West & Green 2024).

Nitrogen and phosphorus pollution

Nitrogen and phosphorus pollution is currently out of scope for the GEIC indicator, but work is underway to scope out the potential for its addition in future. In theory, the limits explored in Section 3.3 could then be applied (~ 6 Tg P yr^{-1} for P and ~ 72 Tg N yr^{-1} for N), if assuming that all N and P inputs are the result of agricultural production. However, it may be more difficult to translate this global limit into national limits (as would be required for presentation in the GEIC indicator). The fact that exceeding the limit in any geographical area would lead to eutrophication in that area, even if on average the global limit was not being exceeded, means that presenting a limit associated with consumption based on, for example, dividing the global limit per capita, would therefore be misleading. It is likely that development of a different and more sophisticated approach, for example assessing whether the limit in each production country was being surpassed and weighting results based on this, similar to what is done currently for the scarcity-weighted water footprint, would be required.

Conclusion

In conclusion, given that none of the limits proposed are entirely impartial and science-based, but all requiring some degree of value judgement and subjectivity, it would misalign with a key aim of the GEIC indicator – being a neutral evidence source – to incorporate them into its presentation directly. However, this section illustrates that it would be possible for those using the data in a policy setting to use the GEIC as a measure against any limits or targets they chose to set themselves – provided that they understood the limitations of doing so, for example not misinterpreting the level of precision in the data available.