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Review

Planetary Boundaries and the Doughnut frameworks: A review of their local operability

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ABSTRACT

The concept of Planetary Boundaries has sparked debate around tipping points and the limits of the Earth System for over a decade. Among the most investigated aspects is how to downscale this global concept to a country level, to make it operative at scales at which decisions are taken and policies applied. Specifically how to achieve applicability locally while keeping global relevance, however, remains unclear. The same is true for the "Doughnut" concept, which builds on the Planetary Boundaries framework and adds a social component to create a "Safe and Just Operating Space" (SJOS) within which humanity should live. This paper reviews these two concepts in detail, focusing on their local operability. Synthesis of the literature reveals that, during the downscaling process, either the global meaning of the Planetary Boundaries or the local characteristics of a country are lost. Further, the SJOS remains a very theoretical concept because a match does not exist between the Planetary Boundaries and the social components of the Doughnut. Identification of this problem therefore suggests that future work should calculate the Planetary Boundaries globally for each ecosystem first, and then downscale them by country. In this way, the global relevance of the Planetary Boundaries would hold, and the framework could apply to local policies. Furthermore, the ecosystem services could link the Planetary Boundaries with the social aspects of the Doughnut, and hence contribute to understanding why a country lies within or outside the SJOS.

1. Introduction

Since the beginning of the Industrial Revolution, the Earth System has experienced changes extending far beyond natural variability (Steffen et al., 2015a), particularly in relation to both the magnitude and the speed of change. The change has been particularly acute in the last sixty years, concurrently with global economic growth and with the substantial increase in the human population. The correlation of global change with human activities is not coincidental, as much evidence exists (Steffen et al., 2006; Millennium Ecosystem Assessment, 2005; Galloway et al., 2008; IPCC, 2013). As human activity has become the main forcing factor on the Earth System, "Anthropocene" has become the term to indicate the geological era in which we live today (Crutzen, 2002). Steffen et al. (2018) also highlighted the role of humanity in shaping the future of our planet, pointing out how our actions are directing toward a "Hothouse Earth", where disruptions to ecosystems, society, and economies will be inevitable and irreversible. The only way to avoid this outcome is a strong transformation of our societies, able to direct us towards a "Stabilised Earth" which would keep us below dangerous thresholds that could trigger cascade effects impossible to revert (Steffen et al., 2018).

The existence of critical thresholds in the functioning of the Earth System is the core concept of the Planetary Boundaries framework (Rockström et al., 2009a and 2009b). Its main aim is to indicate a safe space in which humanity can operate without exceeding tipping points, beyond which sudden and irreversible transformations occur. These transformations would threaten especially the stability that has characterized the Holocene period, in which societies have thrived. The boundaries are conceived as 'guardrails' that keep humanity safe from crossing global tipping points and causing regime shifts with the potential to harm societies as we know them. In fact, the boundaries are set conservatively, to account for uncertainties around the true positions of these global thresholds (Rockström et al., 2009a and 2009b). If the boundaries are not respected, the risk of exceeding a threshold becomes

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real, and if the threshold is exceeded, a regime shift can occur. Table 1 reports the boundaries identified in Rockström et al. (2009a), (2009b) and in the first update of the study (Steffen et al., 2015b), and Fig. 1 shows the current situation, with five of the nine boundaries already transgressed (Persson et al., 2022).

The concept of Planetary Boundaries has stimulated considerable debate. Numerous studies have suggested new boundaries (Running, 2012, 2018), and appropriate variables to define the boundaries (Persson et al., 2013; Mace et al., 2014; Gleeson et al., 2020), and discussed their relevance in global policies (Biermann, 2012; Galaz et al., 2012). Others have focused on downscaling the global boundaries to a regional/country level (Cole et al., 2014; Dearing et al., 2014, Hoff et al., 2015, Lucas and Wilting, 2018, Priyadarshini and Abhilash, 2020, Andersen et al., 2020) and even at smaller scales (Hoornweg et al., 2016; Meyer and Newman, 2018).

The incorporation of a social aspect to the Planetary Boundaries is another development. A planet with sudden changes, unpredictable conditions, and extreme events is less hospitable and it will not be able to feed 9.7 billion people, as forecasted for 2050 (United Nations, 2019), or allow all of them to live a safe and worthwhile life. The "Doughnut" concept subsequently developed (Raworth, 2012) merges a "social foundation" with the Planetary Boundaries (named "ecological ceiling" in Raworth's work). Within the Doughnut model, the outer circle represents the Planetary Boundaries, whereas the social foundation comprises the inner circle. That is, a set of characteristics that make life worthwhile and without deprivation (food security, adequate income, improved water and sanitation, health care, education, decent work, modern energy services, resilience to shocks, gender equality, social equity, and having a political voice). The area between the two circles is the "safe and just space", where humanity should aim to live, not exceeding the Planetary Boundaries and guaranteeing everyone a decent life (Fig. 2). The pursuit of these social priorities does not mean that the environmental aspect must be sacrificed. On the contrary, the environmental issues and the social aspects go hand in hand, and the idea of the Doughnut is an easy image that can address policies in order to gain both goals.

Many interactions exist, in fact, between the Planetary Boundaries and the Social Foundation. Environmental stress can exacerbate poverty and *vice versa*, for example, and policies aiming to reduce environmental pressure, if not well designed, can exacerbate poverty and *vice versa*. The safe and just operating space (SJOS) for humanity is meant to promote those policies that aim both to stay above the Social Foundation and below the Environmental Ceiling. Since its introduction in 2012 (Raworth, 2012), the idea of the Doughnut has received much attention. The easy and appealing concept and the adaptability of the Doughnut have stimulated interest from different actors (from policymakers to Non-Governmental Organisations, to academia). They have tried to downscale it to countries (Cole et al., 2014; Sayers et al., 2014), regions (Dearing et al., 2014), cities (Amsterdam City, 2020) and companies (Houdini, 2018).

Several aspects, however, remain unclear. First is how to use the Planetary Boundaries and the Doughnut concepts together to implement policies that account for both the global scale of the Planetary Boundaries and the local scale to which they can be implemented, toward living with the SJOS. At the same time, effective policies aimed at the future, require a clearer understanding of the trajectories of the Planetary Boundaries and their tipping points, not just snapshots of current situations. Finally, although most of the Planetary Boundaries and aspects of the social foundation already have indicators, the two borders of the Doughnut are unrelated to one another, and an indicator is not yet available to link them together and assess where we lie in the SJOS.

This paper reviews the development of the Planetary Boundaries framework, focusing in particular on the aspects that deal with the downscaling issue and the relation with the social foundation to address the gaps in knowledge.

The review is organized around three key questions:

Table 1
Biophysical domains identified by Rockström et al., (2009) and by Steffen et al. (2015) with the variables that describe them and the correspondent boundaries.

BOUNDARY	Rockström et al. (2009)	Steffen et al. (2015)
Climate change	-Atmospheric [CO_2] (ppm) BOUNDARY: **350 ppm CO_2** (350–550 ppm). - Energy imbalance at top-of-atmosphere (W m^{-2}). BOUNDARY: **+ 1,0 W m^{-2}** (+1,0 – 1,5 W m^{-2}).	-Atmospheric [CO_2] (ppm) BOUNDARY: **350 ppm CO_2** (350–450 ppm). - Energy imbalance at top-of-atmosphere (W m^{-2}). BOUNDARY: **+ 1,0 W m^{-2}** (+1,0 – 1,5 W m^{-2}).
Stratospheric ozone depletion	Stratospheric O_3 concentration, Dobson Units (DU). BOUNDARY: **< 5% reduction compared to pre-industrial level of 290 DU** (5–10% according to the latitude).	Stratospheric O_3 concentration, DU. BOUNDARY: **< 5% reduction compared to pre-industrial level of 290 DU** (5–10% according to the latitude).
Biogeochemical flows: N	Amount of N_2 removed from atmosphere for human use (MtN $year^{-1}$). BOUNDARY: **35 MtN $year^{-1}$** (25–35%).	Global: Industrial and intentional biological fixation of N. BOUNDARY: **44 MtN $year^{-1}$** (44 – 62 MtN).
Biogeochemical flows: P	Inflow of phosphorus to ocean, increase compared with natural background weathering. BOUNDARY: **< 10 ×** (10 × - 100 ×).	- Global: P flow from freshwater systems into the ocean. BOUNDARY: **11 MtP $year^{-1}$** (11 – 100 MtP $year^{-1}$). - Regional: P flow from fertilizers to erodible soils. BOUNDARY: **3.72 Mt $year^{-1}$** (3.72 – 4.84 Mt $year^{-1}$).
Land-system change	Percentage of global land cover converted to cropland. BOUNDARY: **≤ 15% of global ice-free land surface converted to cropland** (15–20%).	- Global: area of forested land as % of original forest cover. BOUNDARY: **75%** (75 – 54%). - Biome: area of forested land as % of potential forest. BOUNDARY: **tropical biome 85%** (85 – 60%); **temperate biome 50%** (50 – 30%); **boreal biome 85%** (85–60%).
Rate of biodiversity loss	Extinction rate, extinctions per million species per year (E MSY^{-1}). BOUNDARY: **< 10 E MSY^{-1}** (10–100 E MSY^{-1}) .	Changed with INTEGRITY OF BIOSPHERE. -Genetic diversity: extinction rate; E MSY^{-1} = extinction rate per million of species per year. BOUNDARY: **< 10E MSY^{-1}** (10–100E MSY^{-1}). -Functional diversity: Biodiversity Intactness Index (BII). BOUNDARY: **90%** (90 –30%).
Global freshwater use	Consumptive blue water use (km^3/year). BOUNDARY: **4000 km^3 $year^{-1}$** (4000 – 6000 km^3 $year^{-1}$).	- Global: Maximum amount of consumptive blue water use (km^3 $year^{-1}$). BOUNDARY: **4000 km^3 $year^{-1}$** (4000 – 6000 km^3/year). - Basin: Blue water withdrawal as % of mean monthly river flow. BOUNDARY: **25%** (25–55%) for low flow months; **30%** (30–60%) for medium flow months; **55%** (55–85%) for high flow months.
Chemical pollution	For example, emissions, concentrations, or effects on ecosystem and Earth System functioning of persistent organic pollutants (POPs),	Changed with NEW ENTITIES.**No control variable currently defined.**

(*continued on next page*)

Table 1 (*continued*)

BOUNDARY	Rockström et al. (2009)	Steffen et al. (2015)
	plastics, endocrine disruptors, heavy metals, and nuclear wastes. BOUNDARY: **not quantified.**	
Ocean acidification	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag}). BOUNDARY: **≥ 80% of medium pre- industrial level** (≥80 - ≥70%).	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag}). BOUNDARY: **≥ 80% of medium pre- industrial level** (≥80 - ≥70%).
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis. BOUNDARY: **not quantified.**	- Global: Aerosol Optical Depth (AOD), but much regional variation. BOUNDARY: **not quantified**. - Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study. BOUNDARY: South Asian Monsoon as a case study: anthropogenic total absorbing and scattering) **AOD (aerosol optical depth) over Indian subcontinent of 0.25** (0.25–0.50); absorbing (warming) AOD less than 10% of total AOD.

1-How can one downscale a global concept (with physical borders) for operability for a country (within political borders)? (Section 2).

2-What is the role of interactions among different boundaries? (Section 3).

3-Can the concept of ecosystem services help to downscale the Doughnut and define the life within the SJOS? (Section 4).

By synthesizing knowledge around these questions, we aim to reveal the obstacles that still prevent the application of these important concepts at wide scale in the real world. Such insight also helps to identify ways to overcome the obstacles.

2. Making the Planetary Boundaries operative

As Planetary Boundaries are a global concept, as suggested in the name itself, downscaling might be unjustifiable or unnecessary. Staying within the Planetary Boundaries should help to prevent abrupt shifts capable of putting at risk critical Earth System processes or eroding its resilience (Rockström et al., 2009b). If one keeps this definition, downscaling the boundaries seems a distortion of this idea. Steffen et al. (2015b) clearly stated that “The Planetary Boundaries framework is not designed to be downscaled or disaggregated to smaller levels, such as nations or local communities”. Nevertheless, the fact that policies are developed and applied locally, within political borders, has led to the development of many downscaled versions of the Planetary Boundaries (for example Nykvist et al., 2013; Hoff et al., 2015). Although these efforts might drive the concept of Planetary Boundaries beyond their initial scope, they offer the advantage of applicability from a policy perspective. As highlighted by Nilsson and Persson (2012), international environmental governance has not always been effective, and multi-level governance is needed to effect change. In particular, when linking the social foundation to the Planetary Boundaries, social indicators do not depend only on the health of the Earth System as a whole but are also deeply influenced by local policies and local environmental conditions. Hence, a country perspective that accounts for local aspects and circumstances is particularly useful when exploring the Doughnut concept (Drees et al., 2021). From a pragmatic point of view, the ability to downscale the boundaries is necessary to make them operative.

A strand of the Planetary Boundaries framework, aimed at making them operational, is the use of footprints. Fang et al. (2015) have highlighted the complementary nature of Planetary Boundaries and environmental footprints, including the benefits of using them to implement each other. If, from one side, the environmental footprint can measure the impacts of human activities, on the other side, the Planetary Boundaries give a reference value to the footprints. Footprints have been developed to calculate different impacts, which now cover most of the Planetary Boundaries: carbon footprint (Wiedmann and Minx, 2008), water footprint (Hoekstra and Mekonnen, 2012), land use footprint (Weinzettel et al., 2013), chemical footprint (Sala and Goralczyk, 2013), nitrogen footprint (Leach et al., 2012), phosphorus footprint (Wang et al., 2011) and biodiversity footprint (Lenzen et al., 2012). Vanham et al. (2019) have made this relationship clearer, showing how different footprints relate to the Planetary Boundaries framework. Some studies have used footprints to downscale the Planetary Boundaries to a national level (Dao et al., 2015; Hoff et al., 2015; Häyhä et al., 2018; O’Neill et al., 2018). This approach has the advantage of being very flexible. A country can, in fact, calculate footprints with a production approach (considering the environmental impact of what is produced within a country), but a consumption approach can also consider the impact of the products imported in a country, which allows highlighting the impacts generated somewhere else by the internal consumption.

Although the use of footprints has many advantages and can track a country’s pressure globally, it is not yet fully suitable for the boundaries with a regional component, because most of the footprints do not account for regional contexts (Häyhä et al., 2018). In fact, according to Steffen et al. (2015b) and Häyhä et al. (2016), the Planetary Boundaries comprise two categories: first, those directly related to a planetary threshold, where what matters is the absolute magnitude of the pressure no matter where it occurs (climate change, ocean acidification, ozone depletion and novel entities); and second, boundaries that operate at regional scales but that become a global issue when aggregated (biodiversity integrity, biogeochemical flows, land-system change, freshwater use and aerosol loading). In the first case, one can compute national boundaries by simply dividing the global budget among the different countries. In the second case, information about local scarcity, vulnerability, hot spots, and so on are important and must be considered.

Although for the first category of boundaries, the downscaling process might seem straightforward in theory, when it comes to practical application, some obstacles are apparent to overcome, in particular equity issues. The main problem is how to distribute the global budget among countries. Lucas et al. (2020) have explored the remaining budget of the European Union (EU), United States (USA), China and India in relation to some of the Planetary Boundaries. They have clearly shown that the choice of the sharing principle can lead to very different outcomes. Hjalsted et al. (2021) reported the same conclusion for the dairy industry in India, Denmark and at the global level by calculating their position in the safe operating space. Additionally, while the scientific concept of Planetary Boundaries is “normatively neutral”, its operationalization is not, because it depends on the risks that humankind is willing to take (Biermann, 2012). In this regard, each country may have a different perspective. As Downing et al. (2019) explained, the Planetary Boundaries define a safe operating space for “humanity”, but this humanity comprises very different actors, whose different needs, behaviours and impacts must be understood to successfully apply this concept. This is, for example, what happened during the negotiations for the Paris agreement (Paris Agreement, Treaty no XXVII-7, 2015). While for some countries, limiting the increase of temperature to 2°C was considered a reasonable target, other countries that would suffer major risks (especially small island countries) pushed for a target of 1.5 °C.

If the operationalization process is complicated for this type of boundaries, it is even more so for the boundaries with a regional

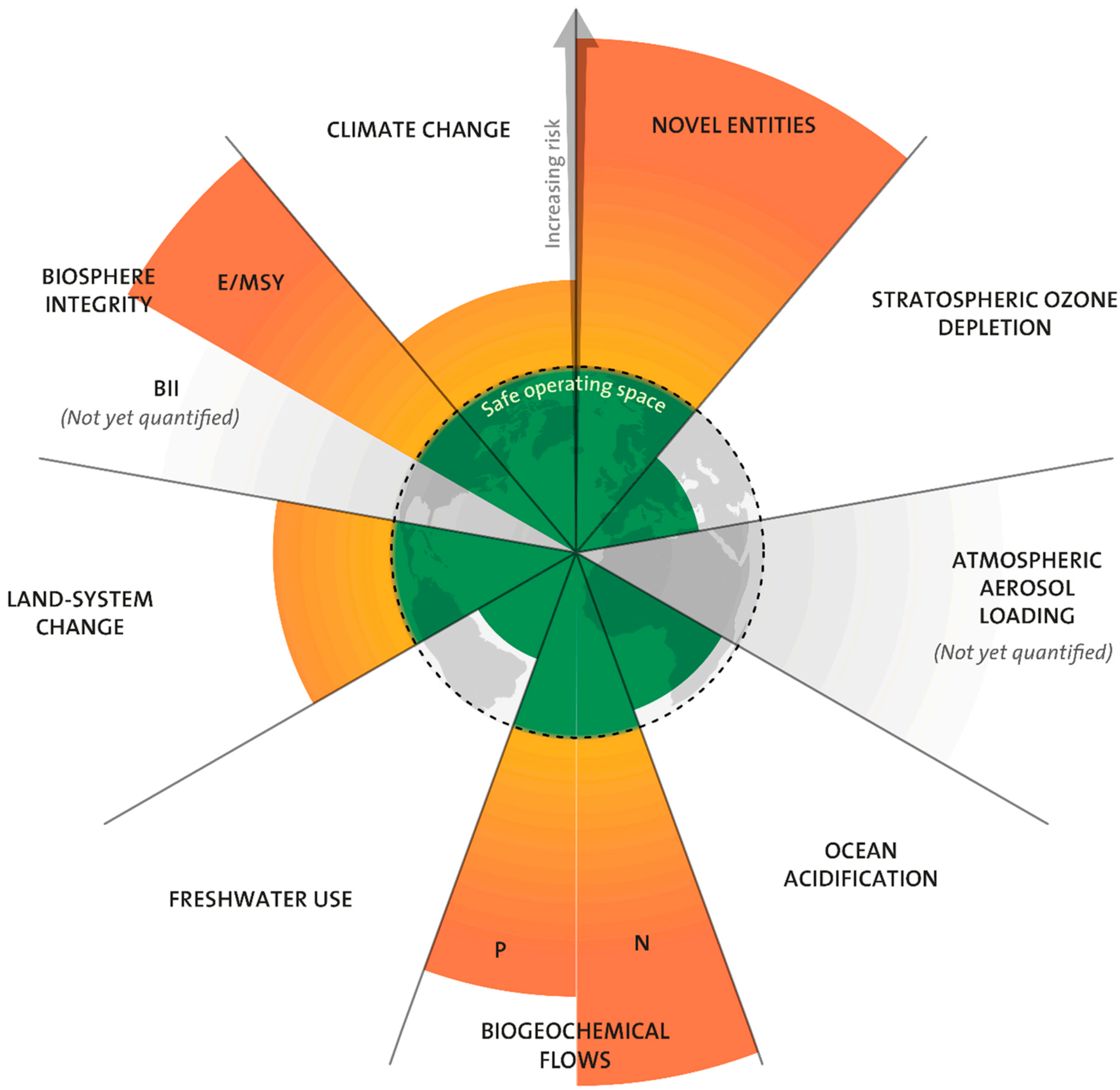

Fig. 1. The dashed circle represents the safe operating space identified by the Planetary Boundaries and the coloured areas indicate the current position in their respect. Green means that the boundary has not been exceeded, while orange means that the boundary has been exceeded. The more the boundary has been exceeded, the bigger the orange area. Licenced under CC BY 4.0 Credit: "Azote for Stockholm Resilience Centre, based on analysis in Persson et al. (2022) and Steffen et al., 2015". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

component. A further step is necessary, not only on how to share the safe operating space but also how to downscale the boundary taking into consideration any spatial heterogeneity. Almost all the past attempts at downscaling the boundaries have focused on either the local or global points of view. On one side, Nykvist et al. (2013), Hoff et al. (2015), Dao et al. (2015), Lucas and Wilting (2018), Andersen et al. (2020) and O'Neill et al. (2018) downscaled the Planetary Boundaries for Sweden, the EU, Switzerland, the Netherlands, New Zealand and 150 countries respectively. They used different top-down approaches that followed the original framework (with some omissions and some changes), without considering regional conditions. On the other side, Cole et al. (2014), Dearing et al. (2014) and Cole et al. (2017) downscaled the boundaries for South Africa, two Chinese regions, and single provinces of South Africa, considering national, regional and provincial peculiarities, but without a strong link to the global picture and with the original boundaries. Comparing Cole et al., (2014, 2017), the need to account for regional heterogeneity for some boundaries clearly emerges from the fact that, in the same country for some domains, the boundary is exceeded at the provincial level, although the national boundary is not. Finally, Priyadarshini and Abhilash (2020), downscaling the boundaries for India, kept continuity with Rockström et al. (2009a), (2009b) and/or Steffen et al. (2015b) when possible (for land-system change and freshwater use), but the safe operating space that they delineated is still more focussed on shaping the boundaries using the current national policies, instead of using the Planetary Boundaries framework to set local policies which include global implications.

In reviewing the application of the freshwater Planetary Boundary, which has a strong regional component, Bunsen et al. (2021) came to the same conclusion. Studies published so far either use a per-capita approach that assigns a value derived from the global threshold, whether it can have consequences on the stability of the Earth System or not, or they calculate a local boundary that ignores the global relevance of the concept. Only Zipper et al. (2020) have developed a framework for the regional application of the freshwater Planetary Boundary. This framework is able to combine both a fair share based on the global boundary and a local safe operating space based on locally relevant control and response variables. They divided the water Planetary Boundary into six sub-boundaries as per Gleeson et al. (2020), which reflect the different functions of water within the Earth System, and represent five different stores of water (atmospheric water, soil moisture, surface water, groundwater and frozen water). Each store of water can either have a boundary only at the global/local level, in which case

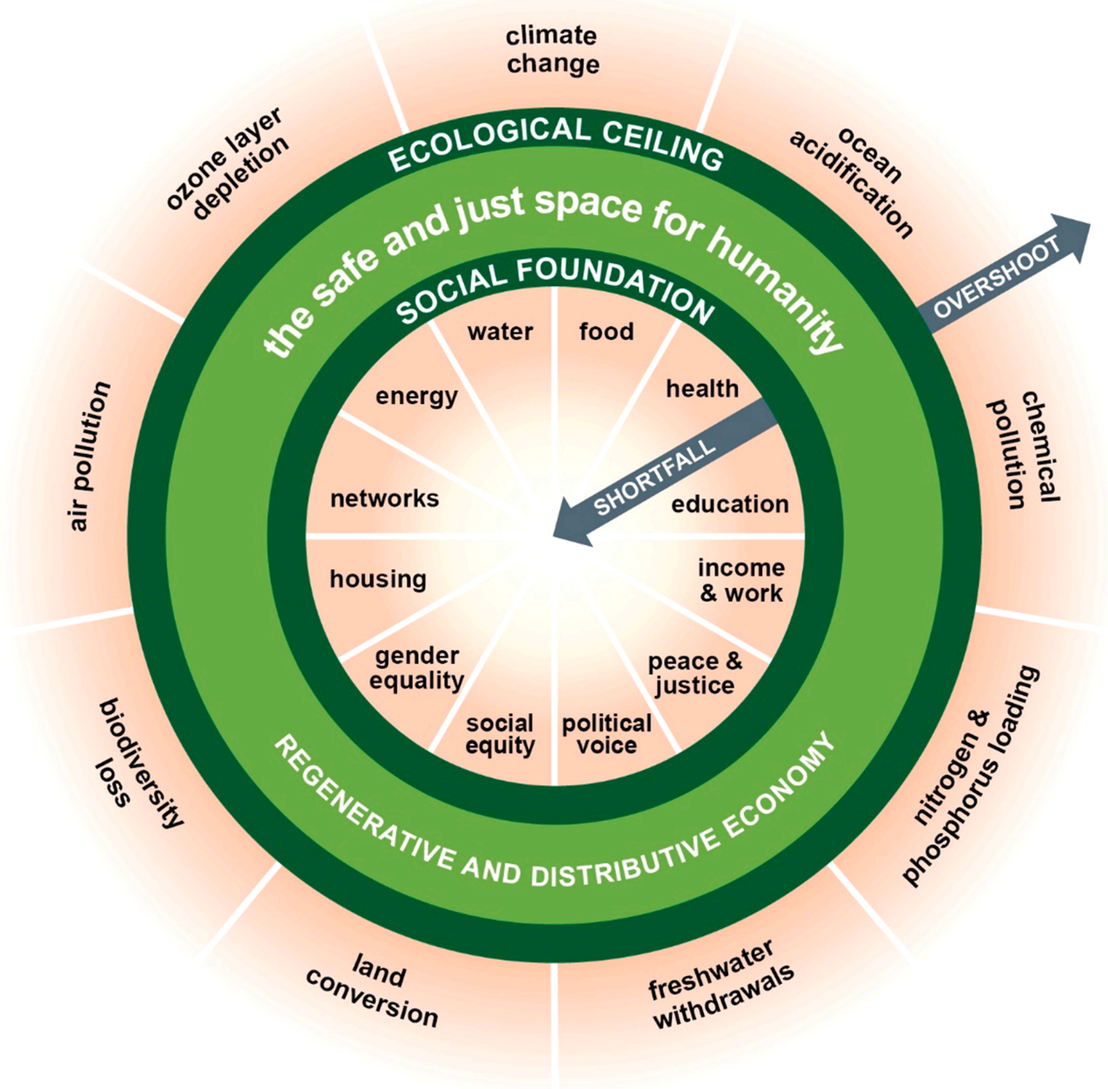

Fig. 2. Illustration of the Doughnut. The green area is the safe and just operating space, defined by the environmental ceiling on the outside and by the social foundation on the inside.
Source: Doughnut Economics Action Lab (DEAL). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

only the relevant boundary will be used, or it can be relevant at both scales. In this case, if the control variable of the boundary is different for the global and the local scale, two boundaries will result, with two different control variables. If the control variable is the same, the more conservative boundary will be selected. This framework has not been applied yet except in a theoretical way, and the control and response variables have been defined only for a particular case study (a Colombian wetland with a mangrove ecosystem).

A recent study by Zhang et al. (2022) has tried to set the local Planetary Boundaries for the Chinese industrial sector. It combined a bottom-up approach that aggregates the environmental performances of the industries at the provincial level through their environmental footprint intensity, with a top-down approach that adjusts the first value if it transgresses the national share of the boundary, derived by applying the egalitarian principle to the global boundary. Although this approach manages to consider the local impact of Chinese industry with an eye toward the global Planetary Boundaries, by using the national share of the global boundaries, it still does not account for the local peculiarities of the Chinese environment and for the eventual insurgence of tipping points at the regional level.

Häyhä et al. (2016), facing the issue of how to bridge the scale between the original boundaries and their national versions, report a lack of consistency in these studies, which is instead necessary if the aim is to support the Planetary Boundaries framework (McLaughlin, 2018). Currently, the only study that compares many countries using the same metrics was conducted by O'Neill et al. (2018), but they used a top-down, per capita approach, not considering regional diversities.

The problem with boundaries that have a regional component is that it is not possible to translate a threshold based on biophysical parameters into a boundary for a nation. In fact, each country can host different ecosystems, whose boundaries rarely coincide with political borders. The next section, therefore, reviews the process of downscaling the boundaries at the ecosystem scale.

2.1. Downscaling the Boundaries by ecosystem

Operating at the ecosystem level would be essentially an extension of what Steffen et al. (2015b) already suggested for the land-system change. The boundary is set using the area of forested land as % of the original forest cover, with differences according to the type of forest (tropical, temperate and boreal). In this case, specific global boundaries apply for specific biomes to account for regional differences. Toward applicability at the country level, though, this distinction must be broadened. For example, in a country like Scotland, where ancient native forests had already long gone before the industrial revolution and most of the current woodlands are afforested plantations made of non-native species, this boundary does not appear sufficient. In this case, a land-system boundary that, for example, set a limit of peatlands in a good condition would be much more relevant, not only for Scotland itself, whose territory is more than 23 % peatlands (Bruneau et al., 2014), but also at the global level, considering the internationally recognized importance of peatlands for climate change (Humpenöder et al., 2020). The same argument holds also for the other regional boundaries. A global boundary for freshwater use, for example, that accounted for the diversity of the ecosystems (calibrated on rainforests to avoid the risk of their dieback, or on peatlands to keep a sufficient water table level, and so on) would be easier to downscale for a nation and would help in shaping local water policies that, together, build global resilience. In the same direction, Scheffer et al. (2015) have suggested the definition of a safe operating space for "iconic ecosystems" to help their local management, arguing that it would also build resilience to climate change. The follow-up by Green et al. (2017) started investigating a global boundary for wetlands, accounting also for the interactions among different boundaries. With an ecosystem focus, the boundaries are manageable (see also Section 3) because processes and feedback are better known. In this regard, the "Regime Shift Database" (https://www.regimeshifts.org/) is a very useful tool. It collects many regime shifts documented in socio-ecological systems and those that affect ecosystem services and human wellbeing, at different scales (global, sub-global/regional, local/landscape). This database contains information about drivers, feedback, ecosystem services involved, temporal and spatial scale, reversibility and confidence related to each observed regime shift.

Zipper et al. (2020) showed that integrating local and global aspects of a regional boundary is possible in theory, as in the case of the freshwater boundary. They implicitly developed a direction of focusing on ecosystems, by providing an example focused on a mangrove ecosystem in Colombia and proposing a linkage between a control variable (water salinity) to some thresholds in that particular ecosystem. This variable would differ for evaluating the freshwater boundary in another Colombian ecosystem, but it is presumably similar for the same ecosystem elsewhere.

McLaughlin (2018) also tackled the issue of downscaling boundaries to the local level, developing a regional boundary framework (applied to a county in the state of Washington in the USA, and its related river basin). He created a safe operating space addressing those boundaries with a regional component (land-system change, freshwater use, nitrogen and phosphorus flows and biodiversity). This approach has the advantage of being locally manageable and coherent with the information about local processes, but at the same time, it can be upscaled to broader areas as part of the Planetary Boundaries framework. Despite the fact that this study addressed the scale issue in the opposite way (from a local framework to the global picture), it is based on the same consideration that boundaries should account for ecological processes in homogeneous regions. What this study shows, in fact, is that for the boundaries with a regional component, with a focus on the ecosystem, locally manageable policies can be implemented, maintaining at the same time the global aspect that underpins the Planetary Boundaries framework.

3. Interactions among the Planetary Boundaries

Even though the Planetary Boundaries are derived separately and their thresholds are set independently, many interactions occur among them in reality. The Planetary Boundaries influence each other's thresholds. Although these interactions have been acknowledged since the beginning (Rockström et al., 2009b), they are difficult to quantify and thus have not been applied in practice (Downing et al., 2019). Lade et al. (2020) made a first attempt to address the issue recently. They considered all possible interactions among the different boundaries and tried to quantify them. The study did not claim to inform policies because of the strong simplifications used in their model, but it brought up the importance of the interactions in shaping the safe operating space and revived the debate and research around this point.

The concept of Planetary Boundaries is a way to keep humanity far from hazardous tipping points that, if exceeded, could trigger sudden shifts in the functioning of the Earth System (Rockström et al., 2009b). The literature about tipping points and regime shifts is clear on the fact that a system can be exposed to increasing pressure without showing any sign of change. Then, all of a sudden, the system changes to a different state of equilibrium (Scheffer et al., 2001, Scheffer and Carpenter, 2003; Groffman et al., 2006). What keeps the system away from this tipping point, even when the pressure starts increasing, is its resilience, which external factors can also enhance or reduce (Gunderson, 2000; Scheffer and Carpenter, 2003; Folke et al., 2004). The interactions among different domains are exactly some of the processes that can increase or decrease the resilience of a system, and hence play an important role in setting a boundary.

In peatland habitats, for example, climate change can trigger a shift from a state characterized by *Sphagnum* cover, typical of bogs, to a state where vascular plants dominate (Eppinga et al., 2009). Climate change can, in fact, increase temperature and decrease rainfall, lowering the water table and favouring vascular plants over *Sphagnum*, which needs a waterlogged environment to thrive (Dieleman et al., 2015). But climate change is not the only driver involved, and other conditions can reduce the resilience of the bog system to change and speed up the shift. Nutrient input is, for example, a key factor in the process, because it stimulates vascular plant growth that is otherwise inhibited by *Sphagnum*, which maintains a low flux of nutrients due to a slow decay process (Limpens et al., 2003). In this example, if one considered the climate change boundary alone, the climate threshold that triggers the shift would be less stringent. But, given the interaction with the nutrient input, a lower level of climate change can trigger the shift.

It is also for this reason that the boundaries of Rockström et al. (2009a), (2009b) followed the precautionary principle. The safe operating space is wide enough to include the uncertainties linked, among other things, to these interactions. The boundaries are also set away from the thresholds that could trigger a shift in the Earth System.

Scheffer et al. (2015) also explained this concept by arguing that managing local stressors could enhance climate resilience and contain the negative effects of climate change. In fact, if it is true that multiple stressors can add up and erode resilience, it is also true that alleviating the pressure from one stressor can build resilience. They explained how to create a safe operating space for iconic ecosystems (the Doñana wetlands in Spain, the Amazon rainforest, and the Great Barrier Reef) that are in critical danger primarily because of climate change. By acting on locally manageable stressors, their resilience to climate change could increase, making them less vulnerable to the effects of climate change itself.

After over a decade since the introduction of the Planetary Boundaries framework (Rockström et al., 2009a, 2009b), understanding the interactions among the boundaries is still a high priority to achieve multiple sustainability goals (Häyhä et al., 2018). Discussing the biodiversity integrity boundary, Mace et al. (2014), argued that interactions and feedback should be addressed with more urgency than defining stand-alone measures of biodiversity. Other authors have instead proposed boundaries that include in themselves more biophysical dimensions. Running (2012) suggested adding a boundary for net primary production (NPP) that would be easy to monitor and model. It would incorporate land use, freshwater use, biogeochemical cycles, climate change and impacts on biodiversity. O'Neill et al. (2018) and Priyadarshini and Abhilash (2020) have added the ecological footprint to account for the cumulative effect of different pressures on the environment.

Following the study of Scheffer et al. (2015), Green et al. (2017) started building a framework for wetland management that applies the Planetary Boundaries concept and accounts for some of their interactions. They considered three different domains (climate change, nutrient loading and freshwater use) and assessed their interactions in the wetlands. They argued that, at the ecosystem level where interactions among the boundaries are better known, managing one stressor to enhance the ecosystem resilience and reduce the impact of another stressor is possible.

3.1. Climate change as a core boundary

Among all the boundaries, some are more interconnected than others. Steffen et al. (2015b) have defined climate change and biodiversity integrity as "core boundaries". This is because they influence and are influenced by all the other boundaries, and because a large change in the climate or in the biodiversity integrity could be sufficient to tip the earth system out of the current Holocene state. Lade et al. (2020) found that the climate change and biodiversity integrity boundaries have interactions with all the other boundaries, which contribute around half the strength of all the interactions. This example makes it even more important to consider the interactions that link these two core boundaries to the others.

At a global level, this linkage is more challenging for the biodiversity integrity boundary because of numerous factors. First is its heterogeneous nature. The extinction rate and reduction of the Biodiversity Intactness Index - the two variables for defining the biodiversity integrity boundary - have a different weight on the basis of the species involved (for example the extinction of a keystone species or a top predator have disproportionally high impacts on the functioning of an ecosystem), and on where they are considered (for example, a tropical forest *vs* a boreal forest). This is reflected in the fact that the Biodiversity Intactness Index must be assessed by biomes or over large-scale areas and there is not a single boundary for it (Steffen et al., 2015b). The second factor is the complexity of biodiversity itself, which is governed by a network of relations among different species that act in different contexts and with different combinations of pressures, making it difficult to identify global patterns. Tylianakis et al. (2008), reviewing the literature, have examined how single drivers (climate change, enrichment of carbon dioxide (CO_2), nitrogen deposition, land use change and biotic invasion) affect the interactions between species (mutualism, competition, food webs). They found that the interactions depend heavily on the species involved and on the environmental context. They also argued that these differences are partly due to the fact that changes in multiple drivers can exacerbate or mitigate the effect of a single driver, making the interactions among drivers just as important, although much less studied. Finally, the biodiversity integrity boundary is still perceived by the scientific community as "provisional" or "incomplete". An improvement compared to the first formulation in Rockström et al. (2009a), (2009b), where they considered the extinction rate (with the boundary set at less than 10 extinctions per million species per year), came with the Biodiversity Intactness Index (BII). Scholes and Biggs (2005) defined the BII as "an indicator of the average abundance of a large and diverse set of organisms in a given geographical area, relative to their reference population." Mace et al. (2014) then suggested it as a potential biodiversity boundary. This index has been included in the updated version of the Planetary Boundaries provided by Steffen et al. (2015b).

Although, with the BII, the representation of the biodiversity boundary has improved, which now accounts for the role of biodiversity in the functioning of the Earth-System and includes both global and biome levels, the uncertainty around this boundary is still wide. The relationship between BII and Earth-System responses is, in fact, not fully clear. The scientific community is still pursuing a way to integrate it with a better variable. The boundary itself includes this uncertainty, with the range set at 90–30% of the BII to be maintained (Steffen et al., 2015b). The actual calculation of the current situation against the boundary was initially available only for the South African region, where it has been estimated a value of 84 % of the BII (Scholes and Biggs, 2005). Newbold et al. (2016) then calculated it for all the terrestrial biomes. They found that 9 out of 14 of them have, on average, transgressed the boundary. To calculate the BII, they modelled the response of biodiversity to land use and its related pressures, assessing not only species richness, but also species abundance. This is also a way of considering the interaction with land use change, although a direct link with the land use change boundary does not exist.

The problems with the biodiversity boundary are also evident in attempts to downscale the boundary to the national level. Most studies either did not consider the biodiversity boundary due to a lack of data (Nykvist et al., 2013; Sayers et al., 2014), or it was changed to another variable considered more suitable for the local conditions (Cole et al., 2014; Dao et al., 2015; Priyadarshini and Abhilash, 2020). The need for a better understanding of the relationships between biodiversity and the other Planetary Boundaries is a fundamental factor to consider when assessing the safe operating space and its future trajectory. Until now, however, only a few attempts in this direction have been made, and many other aspects of the biodiversity boundary are not fully understood yet.

Climate change, the other core boundary, is different from the biodiversity boundary in many ways. The boundary is defined through two variables: the total [CO_2] in the atmosphere, which is set at 350 ppm (350–450 ppm considering the zone of uncertainty), and the energy imbalance at the top of the atmosphere, which is set at $+ 1$ W m^{-2} (between $+1$ and $+1.5$ W m^{-2} considering the zone of uncertainty) compared to the preindustrial level. The definition of this boundary is deemed quite robust and has not changed between Rockström et al. (2009a), (2009b) and their update (Steffen et al., 2015b), except for the upper limit of the uncertainty zone, which has been reduced from 550 ppm to 450 ppm. Second, regardless of where an increase or decrease of [CO_2] takes place, the effects on the climate change boundary are the same because what matters is the total amount of CO_2 in the atmosphere. This also makes the exercise of downscaling the boundary much easier than for biodiversity integrity. Agreement exists in the selection of the variable that can be used in this process, which is usually the amount of CO_2 emissions of the country or of the region considered (Nykvist et al., 2013; Sayers et al., 2014, Cole et al., 2014; Hoff et al., 2015; Dao et al., 2015; Häyhä et al., 2018; Lucas and Wilting, 2018; Andersen et al., 2020; Priyadarshini and Abhilash, 2020).

Discussion on how to downscale the climate change boundary has now become a political and equity issue more than a scientific issue. For example, how does one decide the allocation of the CO_2 emissions? Should the past emissions be considered? Should the amount of emissions account for the current welfare of the countries, allowing less developed countries to emit more? Or, is it sufficient to calculate a global *per capita* value that is the same everywhere? Regarding this point, Nykvist et al. (2013) and Hoff et al. (2015) divided the global carbon budget equally *per capita* worldwide and for the next 100 years. Dao et al. (2015) used a hybrid approach by allocating the emissions to the country first (considering also past emissions) and dividing them by the population to calculate a per capita value (which, naturally, changes if the population increases or decreases). Lucas and Wilting (2018) and Andersen et al. (2020) used the remaining global budget to meet the Paris agreement goal of staying below a 1.5 °C increase, and from it they calculated a per capita value, in the first case comparing different allocation approaches, in the second case with an equal per capita approach based on the current population. Cole et al. (2014) and Priyadarshini and Abhilash (2020), instead, used a political boundary represented by the total amount of CO_2 emissions pledged by the South African government in the first case, and by the Indian projected emissions for 2020 under the Paris Agreement in the second case.

Given its robustness and its global nature, which makes it adaptable to different scales, the discussion around the climate change boundary could probably now focus on how to make it operative and useful in the long term. In the meantime, the focus can shift toward the interactions with the other boundaries. This shift means that, instead of having only the present snapshot of the safe operating space, its future trajectories could be explored, using climate change scenarios (for example the Representative Concentration Pathways used also in the most recent IPCC report – IPCC, 2022) to adjust the values of the other Planetary Boundaries. In fact, if climate change is in some measure unavoidable, its effects can be tackled at the local level through targeted actions on the other boundaries, in order to increase the system's resilience (Scheffer et al., 2015). Climate change is, in fact, capable of changing the future size of the safe operating space, lowering the position of the other boundaries. But given that these interactions go both ways, respecting the other boundaries would make this reduction smaller by increasing the resilience of the SOS (Fig. 3). So, if the Planetary Boundaries are usable in policymaking that looks at the future, they would be more valuable if the effects of climate change on them - and *vice versa* - were accounted for. Irrespective of the scale, the key question in this context would be "what are the management options that maximise the safe operating space in a climate change scenario?". This is not a straightforward question to answer, but some studies in this direction would enable the Planetary Boundaries framework to be relevant for policymakers in the long run.

4. Assessing the "Life within the Doughnut" with the help of the ecosystem services

Living within the Doughnut means operating in the space situated below the Planetary Boundaries and above the social foundation. This definition refers to the safe and just space where humanity can thrive without harming the planet, while also fulfilling everyone's basic needs (Raworth, 2012). Put in other words, living within the Doughnut corresponds with achieving all the Sustainable Development Goals (SDGs). In this respect, as the Doughnut concept was developed in 2012, it responded to the fact that no plan was present at the time to put in practice the Sustainable Development Goals (the SDGs were defined only three years later, in 2015). The Doughnut and the Planetary Boundaries, although not mentioned directly, have been influential in

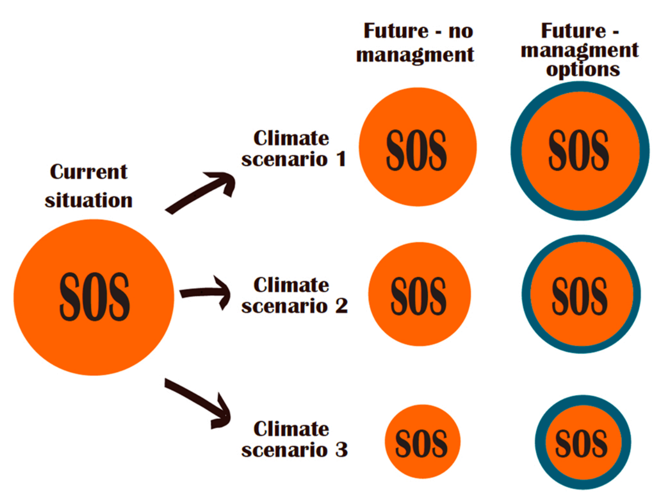

Fig. 3. Conceptual illustration of the interaction of climate change with the other Planetary Boundaries, which together delimit the safe operating space (SOS). Climate change will affect the size of the SOS (orange circles), but management options aimed at staying within the other Planetary Boundaries can make the SOS more resilient to climate change and limit its future reduction (orange plus green circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shaping the SDGs, which include all the aspects of the social foundation and of the Planetary Boundaries, either as a goal or as a target within the goal.

As for the Planetary Boundaries concept, some attempts to downscale the Doughnut have been made to calculate a national or regional SJOS (Sayers et al., 2014; Dearing et al., 2014; Cole et al., 2017). Reviewing these studies, Hossain and Speranza (2020) lamented scarce attention to the social side of the doughnut and the lack of a framework that can standardise the downscaling process. They also highlighted all the challenges when the SJOS is downscaled to a regional level. One of these challenges is the choice of a set of indicators able to capture all the economic, social and environmental processes and that fit the local context maintaining the global relevance of the Planetary Boundaries. Below, we review how quantification of ecosystem services provided by each ecosystem within a particular area (a country, a region, a city) could help define where it sits in relation to the SJOS.

4.1. *Ecosystem services as a measure of life within the Doughnut*

Following the synthesis in Section 2.1, if the Planetary Boundaries are downscaled ecosystem by ecosystem, considering the Doughnut - which adds a social component - the discussion can focus on ecosystem services. Ecosystem services are defined as "the benefits provided by ecosystems that contribute to making human life both possible and worth living" (MA, 2015), which is what, in the end, underpins the SJOS defined by the Doughnut. Both ecosystem services and the Doughnut concept are based on the consideration that the economic and social assets are embodied in the natural assets, and hence they depend on them. This is also in line with the SDGs, whose primary aim is to "promote human dignity and prosperity while safeguarding the Earth's vital biophysical processes and ecosystem services" (United Nations, 2015). Ecosystem services and their fair delivery to humanity could then provide a practical policy tool to assess life within the Doughnut. If Planetary Boundaries exist for each ecosystem, once crossed, they also undermine their ecosystem functions. This in turn puts at risk the ecosystem services that the ecosystem currently delivers, narrowing the SJOS on both sides; the environmental ceiling lowers, as do the services provided to the population, hampering the goals of the social foundation (Fig. 4). To put it another way, to live within the Doughnut, the ecosystems should be maintained in a state that safeguards their services. These services must be adequately delivered to the population. This is a simplification, and it does not account for other services that could eventually emerge from a new configuration of the environment that follows a regime shift. Nevertheless, ecosystem services can be monitored and modelled, offering insights to assess life within the Doughnut, by considering the ecosystem services that are currently available and evaluating their trends. This would not be a substitute for the Planetary Boundaries, but a further metric that could help local governments to track the balance between the opposite sides of the Doughnut. Once a set of global boundaries is defined for an ecosystem, to understand why locally we are/we are not living within the Doughnut, we could first assess the ecosystem services provided by that ecosystem and how they are distributed. The ecosystem services would link the outer and the inner circle of the Doughnut, giving insights on why we are falling short on the social foundation side or why we are exceeding the Planetary Boundaries for that ecosystem. In this case, the problem could be addressed through a better management of the ecosystem itself.

Other studies have also addressed the close relationship between Planetary Boundaries and ecosystem services. Bogardi et al. (2013) used the example of water to show that a safe operating space is defined by planetary resources, ecosystem-based resources and human societies. These aspects together constitute a "balanced triangle of services appropriation", where the needs of societies are met, and the ecosystem and planetary services are kept below their tipping points. Jonas et al. (2014) advocated the need for a roadmap for sustainable land use with the aim of sustaining natural capital and ecosystem services. They

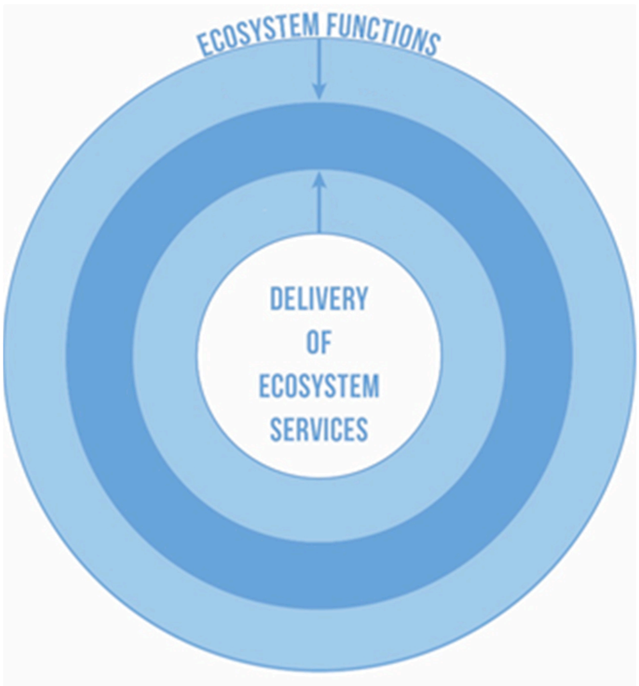

Fig. 4. Conceptual ecosystem Doughnut: Planetary Boundaries allow the ecosystem to perform certain functions which underpin certain ecosystem services, which in turn help humanity to live above the standards of the social foundation (the light-blue Doughnut). When the planetary boundaries are exceeded, the ecosystem functions are lower and so are the ecosystem services provided: the safe and just operating space becomes smaller (the dark-blue Doughnut). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggested a framework that uses the Planetary Boundaries as a global constraint, within which local and regional decisions are accounted for and where a safe socio-ecological space is defined. Mace et al. (2014) suggested a biodiversity integrity boundary based on functional diversity that is biome-specific. They argued that the good functioning of biomes provides ecosystem services that maintain Earth System processes. Even if their scope is broader, they made the link between the biome functionality and the provision of ecosystem services. This, flipping the perspective, give importance to the management of the ecosystem services in relation to the functioning of ecosystems and, at higher level, biomes.

In analysing the literature that developed the Planetary Boundaries concept and the key words used in the papers, Downing et al. (2019) provided some clarity. "Ecosystem services" is a key word only in those papers that the authors defined as "commentary" (*i.e.*, they discussed the concept but did not attempt to use it), whereas in papers that used the Planetary Boundaries concept, ecosystem services were not mentioned. So, while the link between the safe operating space defined by the boundaries and ecosystem services has been discussed, the utilization of ecosystem services as a metric to assess the safe operating space has not been implemented yet.

In a study that combined Planetary Boundaries and ecosystem services, Vargas et al. (2018) suggested linking the Planetary Boundaries framework with ecosystem accounting. They argued that, while the first is focussed on global sustainability, the latter can support national policy-making for sustainable use of natural resources, and that their common ground is the focus on sustainable development. They applied this concept to the Orinoco River basin in Colombia, where the boundaries of land-system change, nitrogen and phosphorus flows and freshwater use provided the basis for a comparison between the extent, condition and capacity to supply ecosystem services, and the supply of ecosystem services of palm oil plantations and tropical forest. The approach of this study is informative from a Doughnut perspective. With ecosystem accounting, socio-economic aspects are considered and an SJOS is defined and addressed in a practical way, where a trade-off exists between the use of ecosystem services and their future availability, but with consideration of global sustainability provided by the Planetary Boundaries framework.

In essence, both the Planetary Boundaries and the ecosystem services concepts have an anthropocentric component. They look at Earth System stability and at the benefits provided by ecosystems with consideration that they are necessary to maintain and/or reach human wellbeing. Importantly, however, ecosystem services can provide a link between the Planetary Boundaries and the socio-economic aspects of the Doughnut. Loss of biodiversity can lead to lower pollination, for example, which means less food. Pollution and high loads of nitrogen and phosphorus can pollute water, which means less clean drinking water availability. The loss of vegetation due to land-use change, combined with high level of pollutants, leads to a less clean air, which leads to health problems, and so on. On the other hand, policies to reduce CO_2 emissions require a change from using fossil fuels, which, if not adequately replaced, mean less available energy. This link is evident particularly for the material aspects of the social foundation (food, water, energy, income), but also the other aspects (*e.g.* equity, political voice, education) are indirectly linked because they are a cause and/or consequence of a fair distribution of the ecosystem services. When the ecosystem services are reduced, the non-material aspects also suffer; *vice versa*, when these aspects are not achieved, less attention is given to the ecosystems, which tend to be overexploited for the benefit of few people. The Millennium Ecosystem Assessment (2003) discussed in greater detail the links and interconnections between ecosystem services and human well-being.

Hence, the SJOS within the Doughnut represents a sort of balance between the social well-being and the environmental constraints. This balance is achievable by maintaining the ecosystem services provided by nature and ensuring that everyone benefits from them.

5. Conclusion

Despite the fact that the Planetary Boundaries have been developed as a global concept, their ability to influence policies requires application at a local scale. Over ten years of research have not yet produced a clear and generalised way to achieve this application. The main obstacle is to account for local characteristics while keeping the original global relevance. Thus, to gain greater clarity on this challenge, we synthesized the literature by considering the problem of scale (Section 2). We addressed the interactions between the boundaries and the role of the climate change boundary in influencing the other boundaries (Section 3). We highlighted the link between the SJOS identified by the Doughnut and the maintenance of ecosystem services, which overlaps in many aspects (Section 4).

Synthesis of the literature on these issues leads us to the following concluding points:

- Although many authors have downscaled the Planetary Boundaries to a country-level, a uniform method that keeps the global framework but also considers regional peculiarities has not been fully developed yet. Other studies, instead, have attempted an ecosystem approach to downscale the boundaries, keeping consistency with ecological thresholds and processes.
- Addressing the interactions among the Planetary Boundaries is challenging, but these interactions often determine an increase or decrease in the resilience of the considered system. This is particularly true for the climate change and the biodiversity boundaries. For the development of sound policies that look into the future, the interactions with climate change – where a certain level of agreement has been reached - should receive more consideration.

- Ecosystem services are often cited when discussing the Planetary Boundaries framework, but only from a theoretical point of view. They are also clearly linked to the idea of the Doughnut. In fact, to live within the SJOS, humanity needs to balance the appropriation of ecosystem services with their maintenance. For these reasons, the concept of ecosystem services has the potential to help monitor the life within the Doughnut.

Hence, we suggest several areas of future studies to meet the outstanding issues identified. First, the downscaling process should not focus on constraining the boundaries, that derive from physical thresholds, within political borders. Instead, we suggest calculating the boundaries for each ecosystem and only then applying them at a country level. This would require a lot of work because meaningful ecosystem boundaries should be set first, but it could be a way to overcome the mismatch between the physical and the political dimensions. With this approach, biophysical thresholds and changes in resilience are investigated, and a boundary can be established with a scientific criterion. Then, using the results of this global exercise, national boundaries for each ecosystem within the country can be set, making them operational where political decisions are being made. National boundaries set in this way could help to establish local policies that aim to preserve global boundaries but that, at the same time, are focussed on the peculiarities of the country itself. This would also make all the national versions of the Planetary Boundaries directly comparable to one another, because they would be based on the same variables and would contribute to staying within the same global boundaries. Second, we suggest including different climate scenarios for the evaluation of the trajectories of the SJOS: climate change influences all the other boundaries and climate scenarios are available and could be used to show how the size of the SJOS could change accordingly. Third, we suggest using the ecosystem services, which constitute a link between the Planetary Boundaries and the social foundation, to practically operate within the Doughnut: acting on their management, we can find a balance that allows us to stay within the Planetary Boundaries and above the social foundation. This is just a theoretical exercise that still needs a lot of work to be implemented in practice, but we think that if refined and applied to many important ecosystems and countries, it could contribute to making the Planetary Boundaries operative, and their downscaled versions coherent and comparable with one another. In this way, the global perspective of the Planetary Boundaries is maintained, and the local environmental and social peculiarity of a nation (or a smaller entity) are considered, as well as the fact that any policy that is going to be implemented will be inevitably influenced by climate change.

Declaration of Competing Interest

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

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