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Synthesis

"Limits" at the human–nature interface: a meta-ethnographic review

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ABSTRACT. Sustainability issues are increasingly viewed through the lens of environmental and sociopolitical limits. However, so far there is no conceptual cartography of limit-related statements in the scientific literature dealing with nature–society relations. Using an inductive review method conducted within an interdisciplinary research team, we define ten synthetic constructs about limits at the nature–society interface. They reveal the vibrancy of this literature, which is extremely rich in terms of disciplinary backgrounds, conceptions of nature, themes of concern, and ways forward. We map out this diversity along two structuring axes—view of the science–policy interface and epistemological stance—and provide two distinct insights based on it. The first one argues for the progress in mutual knowledge and self-reflection among scholars investigating these multiple limits. The second suggests that a "limit field" is emerging, where systems thinking, transdisciplinarity, soft quantification, and integrative general-scope knowledge arise as legitimizing criteria.

Key Words: *environmental governance; environmental justice; environmental limits; field theory; meta-ethnography; planetary boundaries; social-ecological system; sufficiency; systematic review; thresholds*

INTRODUCTION

Academia has long scrutinized the limits of human–nature systems. Thomas Malthus's 1798 theory of population growth is widely regarded as the first formalization of the idea that human society's dynamics are limited by the availability of natural resources. One hundred and seventy years later, the "Limits to Growth" report by the Club of Rome (Meadows et al. 1972) emphasized the dangers of overexploiting natural resources. Building on this legacy, the recent scholarship on "overshooting limits" has shifted the focus from resource availability to threats to social-ecological functioning and the long-term ability of ecosystems to reproduce themselves in the face of disturbances. This scholarship belongs to sustainability science, which combines ecology with earth and social sciences using a systemic approach. Sustainability science indeed embraces an integrative ambition, transcending disciplines to better grasp grand or planetary challenges and trigger political action (Reid et al. 2010).

In line with this ambition, key concepts associated with limits and their overshooting—such as the "Anthropocene" (Crutzen and Steffen 2003), the "great acceleration" (Görg et al. 2020), "planetary boundaries" (Rockström et al. 2009*a, b*); "Earth habitability" (Horton et al. 2021), "tipping points" (Donges et al. 2017, Milkoreit et al. 2018); and the "doughnut economy" (Raworth 2012)—have attracted wide attention and have been discussed beyond academia. A self-reinforcing circle of scientific and political popularity has been set in motion. Unfortunately, in capturing the spotlight, the dominant conceptualizations of limits to sustainability have inadvertently overshadowed other conceptualizations of material, ecological, and sociopolitical limits at the society–nature interface. This monopolization is contested (Brown 2017, Biermann and Kim, 2020, Brand et al. 2021), yet a clear overview of alternative theoretical constructs and their relationship to prevailing notions of limits remains unavailable.

Several authors have attempted to contextualize this recent literature on limits, emphasizing the existence of distinct approaches as well as areas of convergence and filiation (de Grenade et al. 2016, Butler 2017, Scheidel and Schaffartzik 2019, Gupta et al. 2021). However, (1) a systematic analysis of the structure of this literature showing the degree of coherence and differentiation among scientific productions and their major focal points, and (2) a clear elucidation of the diverse theoretical constructs on "limits" along with their specific stances on nature–society, epistemologies, and positions in the science–policy interface are still lacking. The present study aims to address these gaps, hence promoting openness and reflexivity among scholars documenting the various limits that constrain human–nature interactions.

To this end, we conducted a three-step, bottom-up investigation using bibliometric tools and meta-analytical methods. First, we identified the underlying structure of the relevant bibliography using semi-automated methods. Next, we examined the content of a sample of articles using a meta-ethnographic approach (Noblit et al. 1988) in order to synthesize the main theoretical proposals on limits at the human–nature interface in this bibliographic corpus. Finally, based on the results of the first two steps, we posited these constructs in terms of epistemology and integration into policy making. We discuss which contributions are at the core of this literature and which take instead the position of alternative constructs. Although our analysis is not grounded in the history and sociology of science, we offer an insight into whether these various academic contributions constitute an emerging interdisciplinary field (Bourdieu 1976, Panofsky 2011). Our cartography of theoretical constructs reveals the characteristics of this latent field: systems thinking as a foundation, transdisciplinarity, soft quantification, and general scope as yardsticks for claiming their specificity and legitimacy.

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MATERIALS AND METHODS

Overview

Our literature review follows three main steps (Fig. 1):

1. Creation of a bibliographic corpus on the theme of the limits shaping human–nature interactions
2. Exploration of the entire corpus using semi-automated methods
3. Generation of synthetic constructs about limits.

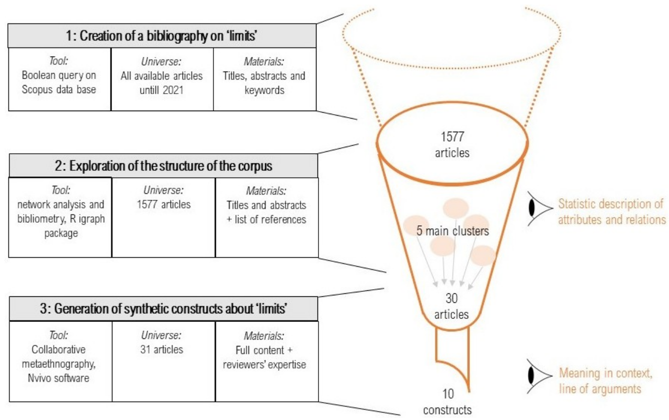
The first two are preliminary steps to grasp some information about how diverse and how structured is the scholarship that uses limits semantics when addressing human–nature interactions. The third one, where the meta-ethnography as such is performed (Noblit et al. 1988), is the central component and expected outcome of the methodological approach. Such an approach required a combination of expertise in several areas (including ecological economics, regional science, geography, public policy analysis, institutional economics, forest ecology, ecological modeling and social-ecological systems research). Each of the three steps are further detailed in the following.

Creation of the bibliographic corpus

We created a Boolean query (i.e., a structured search string combining keywords with operators like AND, OR, and NOT) in the Scopus database to identify articles that potentially belong to the field of limits at the nature–society interface, based on the combination of words they contain in their title, abstract, or keywords. To be included, articles had to combine two types of terms: terms related to limits (limits, boundaries, thresholds, tipping points, endpoints, breaking points, overshoot, exhaust, collapse) and terms related to human–nature interplay (social-ecological, socioecosystem, socionature, sociomaterial, sociometabolic, sociohydrological, ecosocial, human–environment, human–nature, coupled human and nature, ecological-economic). We did not include terms that referred too vaguely to the notion of limits or were mainly used with other meanings (e.g., sobriety, sufficient, availability), those that referred to the environment in a non-specific way (e.g., environment, environmental, resources), or those that dealt with unidirectional flows between social and biophysical compartments (e.g., ecosystem services, nature's contribution to people, environmental degradations, footprints). The timeframe covered the full period available in Scopus, ending in 2021 (our review began in late 2022). Full details of the Scopus query can be found in Append. 1.

We screened the results using two criteria to ensure that the articles were influential: written in English and published in journals in the first quartile of the SCImago[1] Journal Rank (all disciplines combined). This choice has the consequence of offering a biased view of the scientific production on the subject, favoring research communities that use English and publish in international journals (rather than other publication media). We can infer that the picture produced is therefore Western-centered and detrimental to humanities—which indeed reflects broader power relationships in the academy. However, based on our own expertise, we checked that more marginal or dated perspectives about limits at the society–nature interface (spaceship Earth, civilizational collapse, etc.) were still represented in our results.

Fig. 1. A meta-ethnography of the theme of limits in human–nature research in three steps.



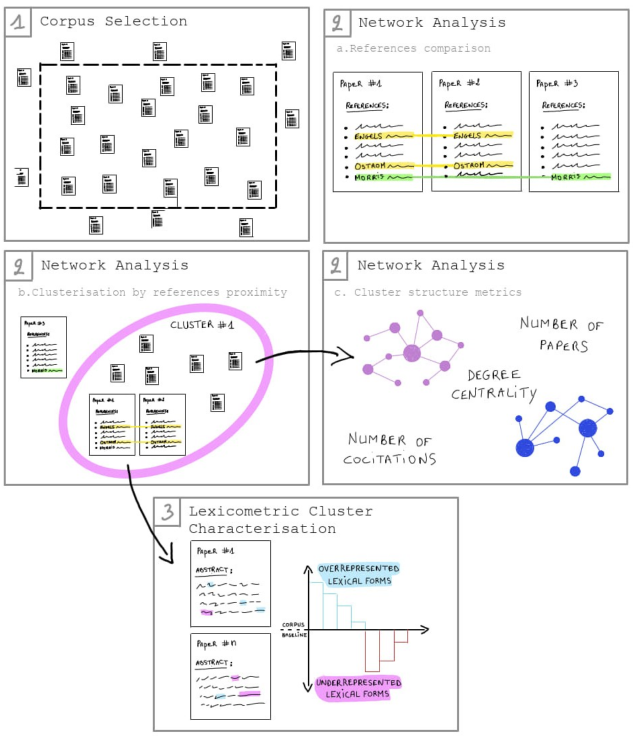
Semi-automated analysis of the corpus and clustering

We use semi-automated analyses of the corpus to identify its structure and, ultimately, whether epistemic communities can be observed. A two-step, bottom-up approach has been developed. This approach involves the clustering of literature into groups and then describes their specificities. To this end, we combine network and content analyses of the corpus (Fig. 2).

The initial stage of the semi-automated analysis aims to address the following question: are there epistemic communities that shape the analysis of human–nature limits? Considering that cumulation is the main pattern through which scientific progress occurs (Newig and Rose 2025), we hypothesize that articles dealing with limits build on or contribute to specific bodies of literature, and if so, share common patterns of references. We carried out a network analysis of the reference lists of the papers included in our corpus (Fig. 2, #1) to operationalize this perspective. A tie between two papers (nodes) is counted if they have a common reference (Fig. 2, #2a). Subsequently, the total number of ties between all possible pairs of papers is calculated. Cluster analysis based on these ties within the resulting network of co-references allows us to group papers according to their proximity in terms of common references (Fig. 2, #2b). To define the contours of the different clusters in our network, we used the Leiden algorithm, as implemented in the igraph R software package (Traag et al. 2019). A useful metric to investigate the internal coherence of a cluster is that of average centrality. For a given article, we define centrality as the sum of the link intensity to all other articles within the cluster, minus the sum of the link intensity to the papers outside the cluster, both normalized by the number of possible links. A cluster with a high average centrality shares a high proportion of references, whereas a cluster having a low average centrality uses more diverse influences.

To complement the metrics characterizing the importance and coherence of each cluster (Fig. 2, #2c), we investigated the content of the articles' abstracts in each cluster (Fig. 2, #3). To this end, we conducted a lexicometric analysis. This is operationalized through a keyness analysis that uses statistically significant signed chi-square values to measure co-occurrences and thereby identify lexical forms that are over- or under-represented in each cluster.

Fig. 2. Steps of the semi-automated analysis of the bibliographic corpus.



Lexicometric analysis involves the cleaning and preparation of the text corpus for the sake of comparability. For that purpose, automated R software functions of the Text Mining R package were used (e.g., removal of symbols and punctuation, lemmatization of forms), and a comprehensive dictionary of lexical forms was created prior to the lemmatization process. The collocation model in the Quanteda R package was used to identify the most common multi-word lexical forms in the corpus for inclusion. We arbitrarily set thresholds at a minimum of three occurrences for four-word lexical forms, 10 occurrences for three-word lexical forms and 20 occurrences for two-word lexical forms, in order to retain only recurring multi-word lexical forms. This approach enables the dictionary to standardize various lexical forms (e.g., social-ecological systems, SES, social-ecological system) into a single form (social-ecological system), thus preventing them from being counted separately.

Overall, we assumed that the combination of metrics based on network analysis and lexicometric analysis could provide useful insights on how (and how much) our corpus is structured and offer a greater legibility of the diversity of works related to limits when considering human–nature interactions. This semi-automatic analysis phase offers an initial overview of the corpus and guides the meta-ethnographic analysis that follows (Fig. 1, #3).

Generation of synthetic theoretical constructs

The last methodological step was to delve deeper into the content of the articles and to build an interpretive framework for the diversity of limits encountered during our readings. Among the variety of systematic review methods, meta-ethnography was chosen because it allows for the production of knowledge syntheses based on inductive and interpretive stances, as opposed to more positivist and cumulative methods (Noblit et al. 1988).

Meta-ethnography is currently widely used beyond ethnographical research. Whereas qualitative content analysis focuses on the coding and thematic categorization of raw textual data (Krippendorff 2019), meta-ethnography enables the interpretive translation and synthesis of concepts from multiple qualitative studies to generate new theoretical perspectives (France et al. 2019). In a meta-ethnography, each study, in our case each article, is considered as a unique entity, with little generalizing or comparative power one with the other. The researcher's task is therefore to extract "meaning in context" (Noblit et al. 1988) from the articles rather than to produce summaries. Analogies, metaphors, and organizers are sought, and it is only through multiple translations of statements that a synthesis can be achieved. Statements can be synthesized using various techniques. In our case, we followed a "line of argument" principle (Noblit et al. 1988, Dixon-Woods et al. 2006) and allowed the introduction of our own reflexive elements at the stage of synthesizing theoretical constructs, (i.e., critical interpretive synthesis; Xiao and Watson 2019).

We followed the steps of the Dixon-Woods et al.'s method (2006) and implemented them as follows:

1. Research question: Stated in the introduction.
2. Literature search: Based on our Scopus extraction, we then used the clusters identified by the reference network analysis to generate a sample of articles to analyze. We selected a number of articles to read in each cluster proportional to the size of the cluster.
3. Selection and screening of articles. The precise selection of articles resulted from three criteria: number of citations (as a proxy for the originality and relevance of the article), specificity to the cluster (as a proxy for generating diversity), and relevance for the conceptualization of limits (based on our own expertise). As recommended in inductive methodology, we applied a saturation criterion (i.e., when no novel statements were observed while including new articles) to define when to stop the analysis.
4. Analysis implementation. We organized the analysis of the articles in teams of two researchers with distinct disciplinary backgrounds. After an initial period of inductive coding (using the NVivo software), we organized a workshop to simplify and reorganize the coding tree and to identify a common frame for summarizing key aspects of the articles. Using the new coding tree and summary frame, we re-coded the first set of articles and gradually added new articles, adding and adjusting codes as needed. We coded 30 articles in this way (Append. 2). A code-by-code synthesis was then performed according to the areas of expertise of our team members. At this stage, the addition of new references based on our own knowledge of the literature could be integrated, as recommended in critical interpretative syntheses. Additional stages of reviewing led to our final summary of theoretical constructs on limits.

Although the preliminary steps of creating the bibliographic corpus and exploring it using semi-automated tools (method steps described above; see also Fig.1) have some value in themselves as descriptive tools, in our case, they are mostly instrumental to performing the meta-ethnography. These method steps relying on semi-automated analysis that we detailed above are somehow a refined version, using digital tools, of the steps "literature search" and "selection and screening of articles" mentioned in Dixon-Woods et al. (2006).

The theoretical constructs we identified at the end of the meta-ethnography depict specific visions or types of limits and also address specific concerns about the relationship between society and nature. These constructs are based on statements found in the articles, not on the articles themselves. Therefore, an article could be included in the review even if only part of it is devoted to limits. Similarly, the same article could feed more than one theoretical construct. The coding applied to each article, along with some other characteristics (community of thought, scale of interest, terminology used, etc.), as well as the full description of the theoretical constructs, can be found in Append. 2.

RESULTS

Structure of the corpus

The bibliographic corpus we extracted from Scopus contains 1,577 articles published in 444 different journals, the most prominent of which are *Ecology and Society* (132 papers), *Sustainability* (63), *Ecological Economics* (46) and *Global Environmental Change* (32)—all of which support transdisciplinary and systemic approaches to environmental issues.

We identified five main clusters of articles, which together contain 95% of the corpus. Prominent authors (e.g., Johan Rockström, Carl Folke, Andrea Nightingale, Robert Costanza, to name just a few) were found in different clusters. Table 1 shows descriptive metrics, and Fig. 3 the results of the keyness analysis for each cluster.

The content and size of clusters 1 and 2 indicate the prominence of the resilience perspective in the corpus. Both have their largest share of articles published in *Ecology and Society* and have "resilience" as their most distinctive lexical form. Cluster 1 (259 articles) is notably the oldest (first year of publication = 1991), with a high level of average centrality, a metric that reflects the importance of shared references. The articles use a variety of key terms to describe social-ecological dynamics and governance, whereas, in contrast, historical and data-related terms (estimate, datum, effect, century, model) are particularly absent.

Cluster 2 (258 papers) shows a specific concern with the threats posed by changes in social-ecological systems (vulnerability, threshold, adaptation, dynamic, change, critical) as well as a stronger ecological tropism. It could be considered as derivate from Cluster 1.

Cluster 3 has many characteristics opposite to those of clusters 1 and 2. It is the largest one in number (718 articles) but the lowest in average centrality, and does not resort to the typical vocabulary of the social-ecological systems. Forms referring to anthropogenic changes and ecological transitions prevail (climate, forest, population, land, species) along with those reflecting an empirical concern (estimate, rate, datum, space, early, high, period). This may explain why this cluster is prolific but weakly structured around common bibliographic references.

Cluster 4, with 180 articles, is the one with the highest average centrality, i.e., having the most shared bibliographic references. Most of the articles were published in *Ecology and Society* (34) and in the *International Journal of the Commons* (10). Their prominent themes are environmental governance and the commons, with a vocabulary that explicitly refers to the Bloomington school of thought (institution, common, governance, resource, community). The typical object that forged the commons theory—fisheries—is unsurprisingly overrepresented, whereas symmetrically urban and global concerns stand out by their relative absence. Although considered constitutive of the social-ecological systems research community, this institutionalist perspective has its own internal consistency, at least for articles focusing on limits.

Finally, cluster 5 encompasses more recent literature, as its first publication year is 2009 (median = 2018) (Fig. 2a). It contains 80 papers, mostly published in *Sustainability* and *Ecological Economics*. They seem committed to the science–policy interface (ecosystem services, demand, stakeholder, monitor, management, design, indicator), with a focus on provisioning services: agriculture and water. This may reflect a recent move toward new ways of producing knowledge that are more tightly linked to societal concerns and non-academic actors.

Overall, we identify two highly structured clusters of articles: a rich one revolving around the Resilience Alliance and a smaller one reflecting institutionalist approaches in the filiation of the Ostrom's works. Those two could reasonably be considered as epistemic communities irrigating the reflection on limits. However, we can also notice that a large mass of articles does not exhibit any obvious pattern regarding references or lexicons. This might be because of the polysemy of limit-related terms, which obviously creates a lot of noise in our corpus, even with the precaution we took in creating the Boolean query. Beyond a dichotomy between social and natural sciences, the semi-automated analysis reveals different sources of diversity among articles addressing limits at the human–nature interface: privileged scales of analysis and objects of research, the place of empiricism vs. theory, and the position of the research within the science–policy interface. Such differences highlight the fact that the literature investigated relies on plural epistemologies, with many lead authors navigating between them.

Theoretical constructs about limits

Table 2 summarizes the main characteristics of each of the 10 theoretical constructs identified throughout our meta-ethnography. Their labels result from our own interpretative choices. The detailed description of each construct can be found in Append. 3.

Natural limits

A few articles refer to limits as constraints on the expansion or functioning of the socio-economic system. Such limits are of physical or biological nature—either conceived as "limiting factors" (e.g., the amount of nitrogen in soils [Erisman et al. 2013] or as "limiting processes" [Madrid et al. 2013]). These types of

Fig. 3. Analysis of the clusters in the co-reference network: keyness analysis. In blue: lexical forms that are over-represented in the cluster compared with the whole corpus (graph showing the 10 highest Chi-square scores); in gray: lexical forms that are under-represented in the cluster compared with the whole corpus (graph featuring the 10 lowest Chi-square scores).

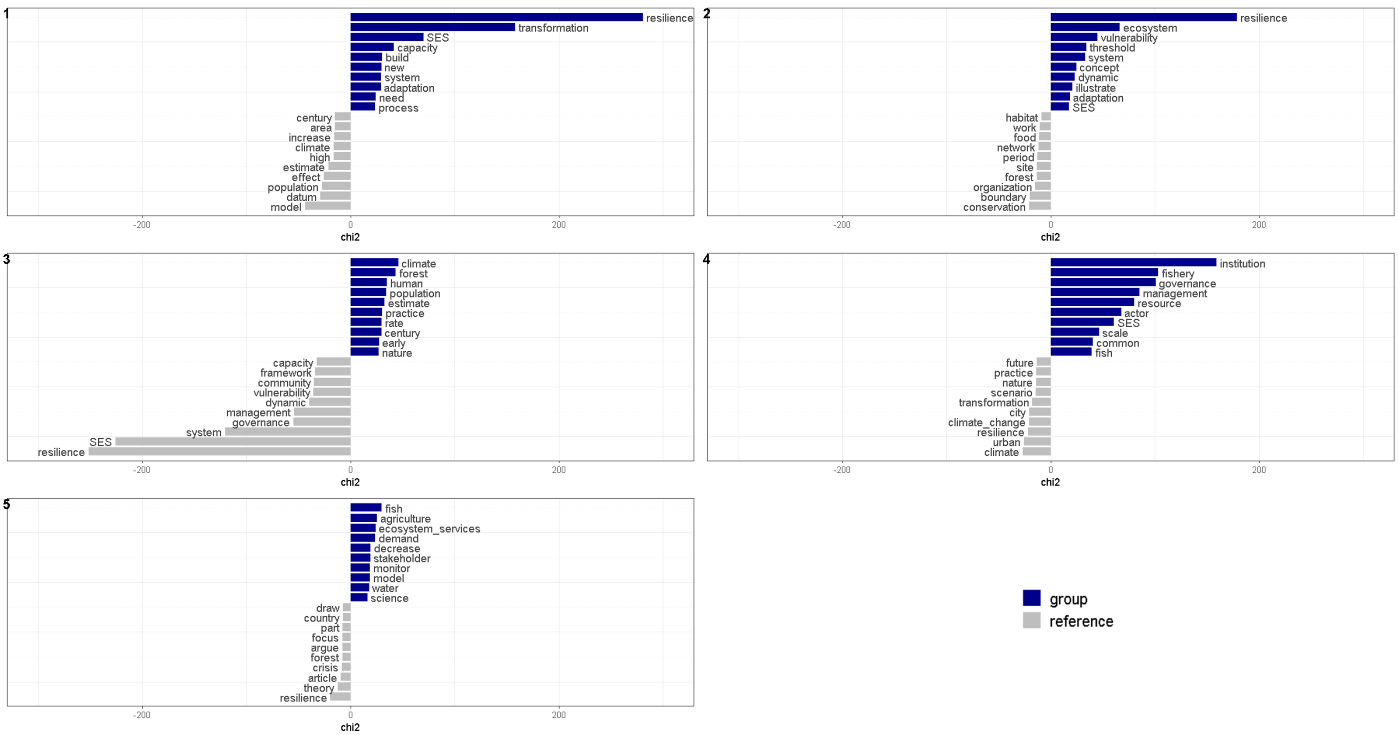


Table 1. Analysis of the clusters in the co-reference network: descriptive metrics.

Cluster	Number of papers	Min. date of publication	Med. date of publication	Centrality score	Mean number of edges
1	259	1991	2015	0.300	124
2	258	1997	2016	0.156	92.6
3	718	1993	2016	0.008	25.6
4	180	1998	2016	0.354	139
5	80	2009	2018	0.230	92

limits consider a finite world: either absolutely finite in terms of resource stocks, or absolutely limited in terms of rates of production and reproduction of ecosystem flows. The level of these limits is generally related to scientific knowledge and/or “common sense” (Pittock 2019).

“Natural limits” retain an embeddedness and interdependence rationale: the economy depends on the good functioning of social organizations, which in turn depends on the functioning of biological and physical systems. However, resources and ecosystem services are socially constructed through technologies and infrastructures, knowledge, and social demand. Human societies can overcome certain natural limits (e.g., by removing restrictions on resource accessibility) or exacerbate them (e.g., by degrading resources and processes) (Madrid et al. 2013, Cumming et al. 2014). Although driven by biological and physical determinisms, various authors (Madrid et al. 2013, Pittock 2019) express that the quantification of limits remains contextual and value laden, hence difficult to turn into regulations.

Stability edges

Several articles use a conception of limits as the edges of a stability domain, outside of which the functional integrity of a social-ecological system is compromised, and a regime shift occurs. This view of limits is mainly heuristic. The term “edge” indicates that two different modes of system functioning are possible, and that it is difficult to return to the former mode after a shift occurs (quasi-irreversibility). This shift is possible under significant disturbance of external conditions (Folke 2006, Liu et al. 2007) or internal modifications of the system (Horan et al. 2011). Different perspectives on the content of this shift coexist: biotic (Folke 2006, Turner 2010, Barnosky et al. 2012); socio-ecological (Liu et al. 2007, Martin 2015, Osman 2021) and socio-political (Young 2010).

“Stability edges” is the most common category of limits we found, as other categories (e.g., preventive boundaries, threshold values) are based on them. All resort—explicitly or implicitly—to the “resilience perspective” (Gunderson and Holling 2002, Walker et al. 2006) and the consideration of mutual interdependencies and feedbacks between ecosystems and society. Resilience (“the capacity to buffer change, learn and develop” [Folke et al. 2002]) is focused on staying within a known domain of stability, and, at the other

Table 2. Summary of theoretical constructs on limits at the human–nature interface.

Theoretical constructs (our labels)	Short definition	Associated concepts	Examples of source articles
Natural limits	The constraints that nature imposes on social and economic organization, in particular the finite quantity of resources and the limited capacity of ecosystems to provide services to society	Embeddedness, ecological flows and funds, scarcity, resource shortages	Madrid et al. 2013, Pittock 2019
Stability edges	Heuristic or theoretical separation between two different domains of stability for social-ecological systems. Stability edges imply that the functioning of the system on the other side of the edge is radically different, which can be both a threat and an opportunity	Resilience, surprises, irreversibility, hysteresis, adaptive management, system behavior shifts	Folke et al. 2002, Liu et al. 2007, Turner 2010
Critical threshold values	A maximum/minimum level in a control variable of a life-supporting system that, if exceeded/not reached, leads to catastrophic shifts for humans and the current biota at regional or global scale	Holocene–Anthropocene transition, early warning signals, collapse	Barnosky et al. 2012, Dearing et al. 2019
Preventive boundaries	A maximum/minimum level in a control variable of a life-supporting system that is at a safe distance from a catastrophic shift. The determination of the acceptable levels depends on the current knowledge of critical thresholds and risk aversion	Safe operating space, anticipation, uncertainty	Rockström et al. 2009, Dearing et al. 2014
Functional contours	The delineation of a functional perimeter for the management and governance of ecosystems or shared resources; this contour and its adequacy evolve over time	Scale mismatch, social-ecological functioning, configurations	Cumming et al. 2006, Baggio et al. 2016
Institutional bounds	Systems of rules that a community develops over time to allow or restrict the use of resources or ecosystem, thereby ensuring their sharing and conservation	Governance, property rights, conflicts	Naughton-Treves 1999, Ostrom and Nagendra 2006
Benchmark values	An accepted level of an environmental parameter that indicates a problematic exceedance because of its impacts on ecosystem or human health. The values adopted are a mixture of political compromise and scientific expertise	Pre-industrial levels, nutrient/carbon/water cycles, environmental risks	Erisman et al. 2013, Schleussner et al. 2016
Welfare minimums	Minimum values within different welfare domains that ensure that planetary resources and environmental efforts are equitably distributed among societies and that human needs are met	Social justice, human needs, prosperity, resource constraints	Raworth 2012
Self-limitation	A set of social conditions, with minimum and maximum levels, that guarantee a good life for all, including non-humans. The definition of the nature and level of these limits is worked out through collective deliberation	Alternative imaginaries, human needs, democratization, commons	Brand et al. 2021, Koch 2020
Limits of limits	A critical approach to the concepts of limits, emphasizing that they lead to a reification of nature and a separation of living and non-living entities and flows	Bindings, social-ecological agency, socio-nature	Bakker 2010, Ingold 2008

pole, transformability ("the capacity to create untried beginnings from which to evolve a new way of living" [Folke et al. 2011]) is focused on reaching a new domain of stability.

In most cases, shifts are neutral descriptors of a dynamic process, without labeling them as threats or opportunities. In other cases, authors intend to define levers of change toward a desirable system state or to provide insights for maintaining the resilience of a social-ecological system at stake. For instance, Barlow et al. (2014) use mathematical modeling to identify the conditions under which a desirable equilibrium (i.e., the control of forest pest outbreaks) can be reached, whereas Osman (2021) derives a set of precautionary, adaptive, and conversion measures for resilient cities.

The articles that refer to "stability edges" are divided into those that take a purely descriptive-analytical view and those that offer general recommendations for virtuous social-ecological management, such as adaptive management. Specific management measures can also be suggested when a specific problematic situation is tackled, but this case is less common, given the abundance of theoretical contributions (see Append. 2).

Critical threshold values

A number of articles see limits as critical threshold values for the biosphere or System Earth, understood as a life-supporting system. Limits represent a maximum or minimum level of a key variable. The term "critical" refers to catastrophic consequences: not only a threat to human livelihoods and societal development (Folke 2006), but also to the current biota adapted to the stable conditions of the Holocene (Rockström et al. 2009*a*, Barnosky et al. 2012). Although the articles share the common conceptual background of the resilience thinking, there is no question of viewing collapse as a source of opportunity (Folke 2006) or creative destruction (Holling 2001).

Critical threshold values are part of a description of bio-geo-physical phenomena, accessible through the observation and modeling of social-ecological interactions. Thresholds exist as natural laws—"The thresholds in key Earth System processes exist irrespective of people's preferences, values, or compromises" (Rockström et al. 2009*b*)—and are expressed in quantitative terms: they may be known, approached, or still under investigation. The nature and type of thresholds is a matter of concern, both for anticipating impacts and for establishing efficient monitoring methods (Rockström et al. 2009, Barnosky et al. 2012, Dearing et al. 2014). The different shapes of thresholds result from the existence of more or less powerful escalation mechanisms, such as scale jumps or positive feedback loops.

Concerns about critical threshold values are first about selecting, quantifying, detecting, and communicating them. For example, Barnosky et al. (2012) discuss approaches to tracking planetary transitions and detecting warning signals, whereas Rockström et al. (2009*b*) are concerned with defining which processes should be monitored and managed as a priority.

Preventive boundaries
These are the cut-off values in the key processes of social-ecological systems that, according to current knowledge, indicate the approach of critical thresholds values. They are warnings, at best early warnings, in a changing and uncertain world.

The premise is close to that of the sister concept of "critical threshold values": human societies depend on stable (Holocene) environmental conditions to thrive. In contrast to critical threshold values, however, preventive boundaries are normative: they are ceiling values (or lower values in the case of aragonite concentration [Richardson et al. 2023]) that "should not" be transgressed because of the risks involved. The theoretical construct of "preventive boundaries" comes from the seminal work of Rockström et al. (2009*a*) who delineated a "safe operating space for humanity" based on boundaries for nine Earth system control processes.

Dearing et al. (2014) advocate for a multiscale approach in which preventive boundaries should be set not only at global, but also at regional scales. For them, threats to the sustainability of regional socio-ecological systems and local livelihoods may occur before they become a concern at the global level. It is also justified by governance concerns, as natural resource management and socio-economic policies are primarily defined and implemented at the regional and national levels. However, the driving concern remains planetary.

Functional contours
Many articles (Naughton-Treves 1999, Cumming et al. 2006, Ostrom and Nagendra 2006, Young 2010, Madrid et al. 2013, Baggio et al. 2016, Murphy et al. 2021) introduce the notion of limits as a contour or delimitation for institutions governing the environment. These articles assess the level of functionality of these institutions. They tend to ask two questions: (1) Are environmental governance tools adapted to the scope and perimeter of environmental issues? and (2) How can the multiscalar dimension of social-ecological systems be adequately taken into account?

The most salient contribution in this vein is that of Cumming et al. (2006). They refer to "scale mismatch" as a situation in which "the scale of environmental variation and the scale of social organization in which responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost." The idea of successful configuration settings for the governance of common-pool resources also echoes that of functional contours (e.g., Baggio et al. 2016).

Some authors delve into the mechanisms generating mismatches and dysfunctionality between ecological and social systems. Cumming et al. (2006) propose changes in the scale of environmental variation, management organization, or both social and ecological interactions as answers. Young (2010) and Koch (2020) elaborate on socio-political lock-ins that impede adaptive mechanisms to occur in changing conditions, such as "institutional arthritis" and "habitus," respectively. Empirical evidence of long-lasting mismatches completes this picture. Examples include colonial or postcolonial hunting rules (Naughton-Treves 1999, Martin 2015), wildlife conservation parks and strict reserves (Naughton-Treves 1999, Ostrom and Nagendra 2006), and species-centered fishing bans (Murphy et al. 2021). These cases show that a narrow understanding of ecological dynamics can result in ineffective environmental governance systems.

Some authors recommend agile adaptations in the governance system, including increased monitoring and better representation of the social-ecological interplay to avoid mismatches and reach the functional fit of institutions governing the environment. Others take a more political stance, focusing on the social processes that lead to the collective use and care of ecosystems. They argue for setting the political and economic conditions that allow for such collective action.

Institutional bounds
These limits refer to how and to what extent people are allowed to use (hunt, protect, extract...) natural resources. The limit is what different institutions define and set as acceptable behavior, either by force, internal habits or beliefs, or through processes of collective choice.

All contributions (Naughton-Treves 1999, Ostrom and Nagendra 2006, Martin 2015, Baggio et al. 2016, Pittock 2019, Murphy et al. 2021) are based on extensive empirical work, either through direct observation, interviews, or document collection. They focus primarily on the governance side of the social-ecological systems, without examining the ecological or hydrological processes that provide the resources of the community under study.

We use the term "bounds" to emphasize that these limits both constrain uses and bind people together: they take place within complex institutional arrangements[2] that are historically constructed, negotiated, and sometimes contested. This includes, for example, the way elephant property rights in Toro district (Uganda) shifted from symbolic authority holders (spirits and the king) to new formal categories (parks and licensed gun owners) over the course of the 20th century (Naughton-Treves 1999). In other cases, the evolution of institutional bounds is observed as a result of ethical controversies (Frolov 2022). An illustration is the progress and setbacks in Australian water regulation. According to Pittock (2019), they express the confrontation between two opposing socio-political narratives on ecosystem exploitation: the "limits to growth" vs. the "pioneering myth."

Recommendations for action such as co-management are often implied. Authors emphasize the importance of a deep understanding of situations, and the involvement of diverse stakeholders. Some also seek a higher level of generalization (Ostrom and Nagendra 2006, Baggio et al. 2016), in line with the design principles (Ostrom 1990, Cox et al. 2010) elaborated by the Bloomington school of political economy.

Benchmark values
We found three articles (Erisman et al. 2013, Dearing et al. 2014, Schleussner et al. 2016) belonging to environmental science that refer to quantitative limit values aiming to qualify the state of an environmental system. These values define an acceptable maximum level or range for an indicator of interest—N2 concentration admissible for ecosystems or human health (Erisman et al. 2013) or temperature targets of the 2015 Paris Agreement on climate change (Schleussner et al. 2016)—but are not associated with an environmental shift.

Dearing et al. (2014) note that the way in which a benchmark or standard value is defined is based on "scientific, expert or public opinion, through negotiation and tradeoffs." Although these values are not arbitrarily defined, they are not guaranteed to be optimal or scientifically robust. The process of elaborating them is beyond the scope of the articles reviewed, but controversies about the right level for the benchmark can still be raised (e.g., about the 2°C consensus in the Paris Agreement [Schleussner et al. 2016]). The degree of institutionalization varies, but many benchmarks—hence becoming norms—are promoted or enforced by official organizations such as the World Health Organization (Erisman et al. 2013) or the European Union (Dearing et al. 2014).

Welfare minima

Some statements deal with minimum thresholds of welfare indicators, "below which lie shortfalls in wellbeing, such as hunger, ill health, illiteracy, and energy poverty" (Raworth 2017). These limits are called "social boundaries" by their authors and extend the planetary boundaries framework (Rockström et al. 2009), in order to define not only a safe but also a just operating space (SJOS) for humanity (Raworth 2012, Dearing et al. 2014).

The justice criterion emerges in a context where international agreements to reduce the human footprint on the environment are being contested by developing countries and human development NGOs (Raworth 2012, Biermann and Kim 2020). Welfare minima embed an explicit claim to modulate environmental efforts according to responsibilities and to allocate non-renewable resources according to needs (Raworth 2012) while deprioritizing economic growth (Koch 2020).

Welfare minima correspond to quantitative targets based on international norms designed to ensure the absence of basic human rights deprivations. In the original framework (Raworth 2012), as in other applications, the 11 targets relate to the most consensual government priorities for the Rio+20 United Nations Conference, although national and regional assessments are expected to have the greatest policy impact (Dearing et al. 2014). The setting of welfare minimum values aims to guide new perspectives on sustainable and inclusive development (Raworth 2012) and, together with the SJOS, to serve as a "compass" (Raworth 2017) or "barometer" (Dearing et al. 2014) for a just transition.

Self-limitation

This category of limits is represented by statements in a few articles (Koch 2020, Brand et al. 2021), and is colored by a degrowth and relational perspective on human–nature interactions. "Self-limitation" presupposes a resource-abundant (but not unlimited) planet, which is compromised by specific production and consumption dynamics generated by capitalist economies.

Self-limitation is seen as a condition for collective and individual empowerment and vice versa. The authors refer to Görz (autonomy), Bourdieu (habitus), Marx (reproduction of the class structure) or Max-Neef (satisfaction of needs) to give political content to the demand for "self-limitation." "Within societal boundaries and through collective self-limitation, the conditions for a good life do not come at the expense of others' ability to do the same, nor at the expense of the flourishing of future generations or non-human others" (Brand et al. 2021).

The content and level (especially the upper level) of these limits are expected to be debated and negotiated, and open to pluriversal imaginaries. In contrast to institutional bounds, the focus is on the democratization of limit setting—not its historical anchoring—and implies a break with power concentration and the exploitation of nature. Self-limitation expresses an ethical and political stance in which a new social contract is established with non-humans and future generations through collective deliberation and social practice.

Limits of limits

Some articles (Ingold 2008, Bakker 2010, Cote and Nightingale 2012, Brand et al. 2021, Reisman and Fairbairn 2021) endorse a critical social science perspective to develop a "limits of limits" argument. For them, most limit perspectives close and reduce the understanding of human–nature relations or even produce a loss of sense of inhabiting the world (Ingold 2008). These statements echo the criticisms that science and technology studies have already made of the planetary boundaries framework (Biermann and Kim 2020).

Reductionism is a first source of criticism and includes: the narrow scope of the environmental issues deemed noteworthy (Brand et al. 2021), the oversimplification of the drivers of the ecological crisis (Koch 2020, Reisman and Fairbairn 2021), and the "orthodoxy" (Brand et al. 2021) of the proposed solutions. A second source of criticism is the reification of nature as something external to human experience: Ingold (2008) reminds us that we inhabit the world through individual experience and mutual bindings and flows. Finally, most authors deplore the depoliticization of concepts of limits, which is due to the qualification of humanity as a single biological entity (Koch 2020, Reisman and Fairbairn 2021), and the under-representation of power relations and social-ecological agencies (Cote and Nightingale 2012).

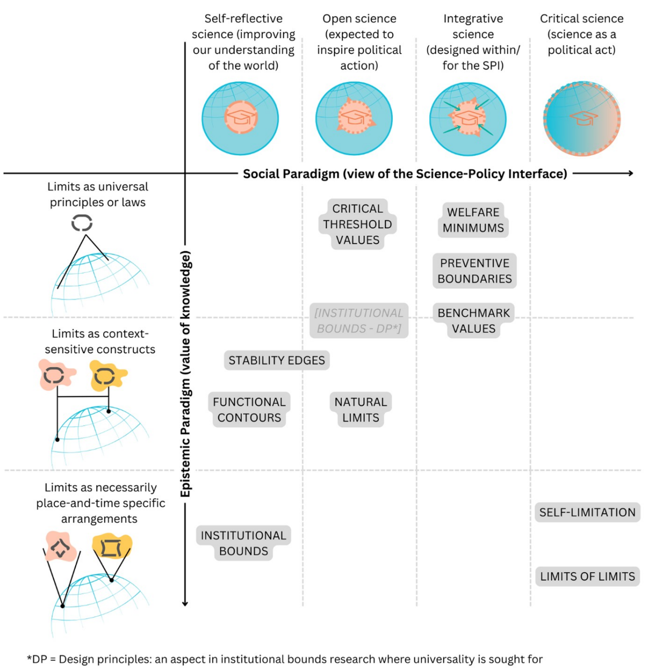
New concepts and ontologies are proposed to promote transformative action: a comprehensive view of socio-nature, with non-humans understood as political subjects (Bakker 2010), the diversification of values, worldviews, and legitimate knowledge about limits (Brand et al. 2021), and a stronger commitment to empiricism (Cote and Nightingale 2012).

Relations and oppositions among limits constructs: an emerging research field?

A wide range of relationships lies within the diversity of theoretical constructs about limits, including oppositions, nuances, commonalities, and filiations. We consider two main axes of differentiation (Fig. 4), reflecting findings from the co-reference network analysis.

The first axis (social paradigm[3]) addresses the place of knowledge production in society. Knowledge production can occur within a semi-closed academic world devoted to representing and understanding the "real" social-ecological world. Alternatively, knowledge production can entail a socio-political and techno-scientific world. In this case, the boundary between values and knowledge disappears, and knowledge production is accepted as the result of complex assemblages between social, natural, physical, and technical entities, rather than as a "pure" or "disinterested" activity. Other positions exist where science and policy operate as distinct spheres of activity, but collaborate to produce the knowledge needed to address

Fig. 4. A cartography of theoretical constructs on limits. DP = design principles; SPI = science–policy interface.



"grand challenges" (Reid et al. 2010). Although sustainability science generally occupies this intermediate position, the academic literature on limits that we analyzed exhibits a broader spectrum of social stances. Furthermore, our cartography reveals that the science–policy interface is appealing, with dominant contemporary constructs on limits located in this quadrant. These constructs increasingly claim to be "boundary objects" (Pickering and Persson 2020), and to provide policy makers with the status of "co-producers" of this knowledge (Balvanera et al. 2020). One aspect of this shift is the prevalence of quantitative references in the most recent theoretical constructs on limits, in contrast to older heuristics regarding limits, such as stability edges, functional contours, and natural limits, which were sometimes considered too vague to yield concrete recommendations (Carpenter et al. 2001). However, this trend toward measurement remains soft, as quantitative indicators and proxies are primarily intended to provide scientific guidance.

The second axis, the "epistemic paradigm," addresses the value and meaning associated with knowledge about limit constructs. When defining limits, scholars may aim to produce universal, reliable, and cross-cutting knowledge about social-ecological dynamics. In this case, they seek knowledge that is valid at the planetary or humanity scale, while considering regionalization or downscaling as important challenges. This is notably the case for the theoretical constructs revolving around the "safe operating space for humanity" (Rockström et al. 2009*a*): "critical threshold values," "welfare minimums," "preventive boundaries," and "benchmark values," according to our typology (Table 2). Other limit constructs address "context sensitivity" (Reyers et al. 2022): they focus on the interplay between contextual specifics and the outcomes of ecosystem management interventions. This stance goes beyond the simple downscaling of general frameworks and is typical of works emphasizing the coevolutionary dynamics between social and ecological systems. This perspective is evident in early research about the resilience of social-ecological systems (Berkes et al. 1998, 2003) and in some strands of ecological economics (Mayumi 2009, Kallis and Norgaard 2010)—although coevolution there has quite a distinct meaning in these two communities. Consequently, the theoretical constructs about limits derived from these backgrounds—such as, "functional contours," "stability edges," and "natural limits"—adopt the same stance of context sensitivity. Finally, in a constructivist epistemology, limits are viewed are situated constructs meaningful only in the context of their creation and use. They are specific to place and time and embed a complex trajectory of construction and change shaped by power relations, cosmologies, and contingencies. This epistemology is found in some of the theoretical constructs rooted in the social sciences: "institutional bounds," "self-limitation," and "limits of limits."

Considering the chronology and distribution of our theoretical constructs along the epistemological and social axes, we can suggest a progressive shift toward stances that seek for generalization or universalization, as well as open and integrative science (Fig. 4). In essence, the worthiest objects of investigation progressively become those that are large and holistic enough to address planetary challenges.

We can clearly identify a high level of interrelations in the constructs that sketch from "institutional bounds" to "preventive boundaries" (bottom-left to up-right corners in Fig. 4). These works share common references to co-evolutionary and co-adaptive processes between human and natural systems, an emphasis on uncertainties and nonlinearities driven by environmental degradation, and a strong focus on the latter's impacts on human livelihoods. Although the case of "institutional bounds" communicates with the other seven theoretical constructs, it probably cultivates its own internal coherence more, according to what we observed in the network analysis (see Fig. 3, cluster 4). We believe this axis constitutes the core of an emerging field of research.

Characterizing these academic productions as a field (Bourdieu 1976, 1991, 2019) highlights the hierarchical structure of relations between scientific protagonists, which creates both attraction and contestation. The positions that scientists hold within a field result from the importance of different forms of capital (economic, political, and symbolic) that they have acquired. According to Bourdieu, there is no such thing as a scientific community (Bourdieu 1991), which structure would be based on "purely scientific" criteria such as refutability, rigor, independence, or novelty. Like any other social field, the scientific field—and its subfields and disciplines—has its "struggles, interests, and distribution of power." However, it also has its specificity. It operates according to an internal logic and system of rules that indicate which methods are legitimate and how to integrate into the field (Bourdieu 1976, 1991). Unlike other fields, the scientific field is however attached to an "illusio" of being "pure" and disinterested (Bourdieu 2019). This "illusio" generates a specific form of capital: the scientific capital. This capital is acquired through publications and institutional strategies, and sets the rules under which scientific competition can occur.

When considering an emerging "limits field," we stress that the diversity of the theoretical constructs identified reflects something more than just different epistemological and operational logics. We also hypothesize that their uneven distribution reveals conservation and succession strategies as well as subversion strategies (Bourdieu 1991, Albert and Kleinman 2011). One such strategy (succession) is building on the heuristics of the resilience perspective, particularly the ideas of alternative stable states and critical threshold values to derive more global and operational concepts. This strategy allows scientists to achieve a higher level of significance based on the broad scope or universality of their contributions as well as their alignment with decision-making issues. According to Albert and Kleinman (2011), the growing involvement of socioeconomic stakeholders in knowledge production indicates a shift in the field's inclusion criteria. These new criteria can be observed as constitutive of transdisciplinary research. The subversion strategy, on the other hand, is embraced by the theoretical constructs of "self-limitation" and "limits of limits," which take a critical stance and establish connection with grassroot movements or non-Western communities rather than with decision makers. Despite their very distinct rationales, they mobilize references that are openly incompatible with the core of the limits field (Marxist theory, eco-feminism, entanglements, etc.) and are also at odds with integrative science and upscaling logics. The appeal of the succession strategy is evident in the integration of parts of the critiques from earth sciences, development studies, and science and technology studies (Biermann and Kim 2020) into new concepts and frameworks associated with planetary boundaries, such as sustainable consumption corridors, (Di Giulio and Fuchs 2014) and planetary commons (Rockström et al. 2024).

CONCLUSION

Our literature review reveals the richness and diversity of theoretical constructs related to limits in the scientific articles dealing with nature–society relations. These constructs have emerged and evolved within a firmly interdisciplinary body of literature, with a 30-yr history. This body of literature is dominated by the resilience perspective, but it is also epistemologically plural, subject to controversy and critique, and is increasingly engaged at the science–policy interface. Mapping out the diversity of these constructs provides a dual reading. First, we demonstrate the vibrancy of this academic literature and encourage researchers to be open and reflective. Understanding "where we speak from" is increasingly considered crucial for sustainability scientists and practitioners (Knaggård et al. 2018, Hazard et al. 2020). Second, we analyze how this diversity is structured, going beyond its mere characterization to explore the possible emergence of a field. We decipher forces of attraction and struggle using the field theory developed by Bourdieu. We demonstrate the influence of succession strategies within the limit field and the development of a particular set of inclusion criteria: system thinking, transdisciplinarity, a preference for measurement, and a pursuit of integrative, even holistic, knowledge.

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[1] SCImago define themselves as "a research group from the Consejo Superior de Investigaciones Científicas (CSIC), University of Granada, Extremadura, Carlos III (Madrid) and Alcalá de Henares, dedicated to information analysis, representation and retrieval by means of visualisation techniques" (https://www.scimagojr.com/aboutus.php).

[2] By institutional arrangements, we mean sets of rules in use operating at different levels, which together define the allocation of use rights to different community members.

[3] The term "paradigm" is used here in the sense given by Piaget (Piaget and Garcia 1983).

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All 10 co-authors: conceptualization, methodology, investigation, validation, writing - review and editing; Sandrine Allain: additionally, project administration, writing - original draft.

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Data Availability:

Data/code sharing is not applicable to this article because no data and code were analyzed in this study. However, all transparency details, including the Scopus query, the full description of limit categories, and the categorization of the reviewed articles are available in the supplementary materials.

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Appendix 1 – Methodological choices for the Scopus query

1. Full query

TITLE-ABS-KEY (

({limits}
OR ("boundary*" AND NOT ({bounded rationality} OR {transboundary} OR {boundary object}))
OR "threshold*" OR "tipping point*" OR "end point*" OR "breaking point*"
OR "overshoot*" OR ("exhaust*" AND NOT {exhaustive}) OR "collaps*")

AND

({social-ecological} OR {socio-ecological} OR {socioecological}
OR "socio-ecosystem*" OR "socioecosystem*"
OR {society-nature} OR {nature-society} OR "socionatur*" OR "socio-natur*"
OR "socio-material*" OR "sociomaterial*"
OR "sociometabolic" OR "socio-metabolic"
OR "sociohydrolog*" OR "socio-hydrolog*"
OR {ecological-economic} OR {economic-ecological}
OR {ecosocial} OR {eco-social}
OR {human-nature} OR "coupled human and natur*" OR {human-environment}))
AND (LIMIT-TO (LANGUAGE,"English")) AND (EXCLUDE ((PUBYEAR,2022) AND (PUBYEAR,2023) AND (PUBYEAR,2024)) AND ISSN (*#List of Q1 journals*)

2. Chosen terms

<u>First set of terms (limits semantics):</u>

{limits} : bounded to {limits} instead of "limit*" to avoid noise (ex. 'our results are limited…', 'there are limitations')

"boundary*" AND NOT ({bounded rationality} OR {transboundary} OR {boundary object}) : This specification is to avoid common terms from the 'boundary' family, which are not relevant for our query.

"threshold*" OR "tipping point*" OR "end point*" OR "breaking point*" : synonyms to 'limits' without ambiguities in their meaning

"overshoot*" OR "exhaust*" OR "collaps*": set of verbs referring to the transgression of limits.

<u>Second set of terms (human-nature interface semantics):</u>

({social-ecological} OR {socio-ecological} OR {socioecological} OR "socio-ecosystem*" OR "socioecosystem*" OR {ecosocial} OR {eco-social}: association of adjectives linking society and ecology

{society-nature} OR {nature-society} OR "socionatur*" OR "socio-natur*": association of terms linking society and nature

{ecological-economic} OR {economic-ecological} : association of terms linking the economy and ecology. It allows to include ecological-economic modelling. We kept the hyphen for 'ecological-economic' to avoid references to the whole ecological economics community.

"socio-material*" OR "sociomaterial*" OR "sociometabolic" OR "socio-metabolic" OR "sociohydrolog*" OR "socio-hydrolog*": Compound terms that relate the social to the physical and material reality. They have their importance for the inclusion of social sciences.

{human-nature} OR "coupled human and natur*" OR {human-environment}: "human and natur*" was a too broad expression, so we specified terms, which we know to refer to the human-nature interface.

3. Exclusion criteria

We limited the results to articles published in journals belonging to the first quartile (all disciplines combined) of the SciMago referencing system and written in English. This choice allows us to favor references that have a stronger influence for the limits field. We have checked that certain openly heterodox journals were however included (International Journal of the Commons, One Earth, the Anthropocene Review...).

At the operational level, the SCOPUS query listing all Q1 journals is too long and crashes the search engine. We therefore proceeded with three series of similar queries, varying the ISSNs of the journals, to cut the list of journals to be included in 3.

These choices unavoidably create biases -exclusion of books and exclusion of non-English written literature – although they reinforce the consistency of our sample of articles.

Note on predatory journals or those with a high self-citation rate: To date, there is no official list enabling us to easily justify the exclusion of certain journals. In our sample, we will find journals with questionable practices that publish a large number of articles.

	1 : TYPE OF CONTRIBUTION	2 : COMMUNITY OF THOUGHT	3 : METHOD	4 : SCALE OF INTEREST	5 : LOCALIZATION OF CS	6 : THEORIZATION	7 : TERMINOLOGY LINKED TO LIMITS	8 : NATURE AS…	9 : RECOM. FOR ACTION	10 : MAIN CATEGORY OF LIMITS	11 : OTHER CATEGORIES OF LIMITS
(MADRID ET AL., 2013)	Methodological and empirical	social-ecological metabolism	Modelling	regional or national	Catalonya (Spain)	Yes	external and internal constraints	resources, ecological fund	Yes	1: Natural limits	5: Contours
(FOLKE ET AL., 2002)	Theoretical	resilience thinking, complex adaptive system	Comprehensive or historical analysis	NA	NA	No	regime shifts	biosphere, including human societies and the economy	Yes	2: Stability edges	
(FOLKE, 2006)	Theoretical	resilience thinking, complex adaptive system	NA	ecosystem	NA	Yes	regime shifts, collapse	ecosystems	Yes	2: Stability edges	
(FOLKE ET AL., 2011)	Position paper	resilience thinking	NA	global, planetary	NA	No	tipping point, threshold, boundaries	biosphere, including human societies and the economy	Yes	2: Stability edges	
(LIU ET AL., 2007)	Theoretical	resilience thinking, complex adaptive systems	Cross-analysis, comparison of CS	ecosystem	6 CS : USA, Brazil, Sweden, Kenya, China	Yes	threshold, system behavior shifts	ecosystem services	No	2: Stability edges	
(TURNER, 2010)	Synthesis	landscape ecology	Review	multiscale	NA	Yes	shifts, threshold	ecosystems, ecological communities	No	2: Stability edges	
(COSTANZA ET AL., 2007)	Position paper	resilience thinking, environmental history	Comprehensive or historical analysis	global, planetary	NA	No	major thresholds, collapse, enveloppe of regularities,	environment, nature including humans	No	2: Stability edges	1: Natural limits

							external limits to social reproduction				
(CUMMING ET AL., 2014)	Theoretical	resilience thinking, social-ecological coevolution	Cross-analysis, compariso n of CS	multiscal e	China, Sweden, Niger	Yes	shifts in ecosystem functioning, traps leading to collapse	ecosystem services, life-support systems	No	2: Stability edges	1: Natural limits
(OSMAN ET AL., 2021)	Synthesis and empirical	Resilience thinking, urban planning	Review and Survey	local communi ty	Japan	No	End points, maximum level of risk exposure, regime shift, shortages of natural resources	environment	Yes	2: Stability edges	1: Natural limits
(MARTIN, 2015)	Empirical	resilience thinking, transition theory	Comprehe nsive or historical analysis	local communi ty	Alaska (USA)	No	transformation and adaptation to hunting limits	subsistence resources	No	2: Stability edges	6: Bounds
(BARLOW ET AL., 2014)	Theoretical and methodologi cal	Forest-pest interaction, coupled human-environment modelling	Modelling	regional	Canada	No	threshold, system behavior shifts	resource, ecosystem	Yes	2: Stability edges	6: Bounds
(YOUNG, 2010)	Theoretical	resilience thinking, environmental governance	Review	multiscal e	NA	Yes	abrupt change, tipping point, collapse, overwhelm, spatial boundaries, crisis	resource, environment	Yes	2: Stability edges	5: Contours
(BARNOSKY ET AL., 2012)	Position paper	global change biology	Review	global, planetary	NA	Yes	critical thresholds leading to state shift	biosphere	Yes	3: Critical threshold values	2: Stability edges
(DEARING ET AL., 2019)	Empirical	resilience thinking, social-ecological coevolution	Comprehe nsive or historical analysis	regional	Shucheng county (China)	No	critical thresholds	ecosystem services	Yes	3: Critical threshold values	2: Stability edges

(ROCKSTRÖM ET AL., 2009)	Theoretical and synthesis	resilience thinking, Earth system science	Review	global, planetary	NA	Yes	planetary boundaries, transgression, dangerous thresholds	key biogeochemical and atmospheric parameters, Earth system (including humans)	Yes	4: Preventive boundaries	3: Critical threshold values
(DEARING ET AL., 2014)	Theoretical and empirical	resilience thinking, social justice	Cross-analysis, comparison of CS	regional	Erhai lake catchment and Shucheng county (China)	Yes	environmental ceiling, social foundations	resources, ecosystem services	No	4: Preventive boundaries	7: Benchmark values 8: Welfare minimums
(CUMMING ET AL., 2006)	Theoretical	resilience thinking, social-ecological coevolution	NA	multiscale	NA	No	boundary; temporal, spatial, functional scales	ecosystems, ecological processes	Yes	5: Contours	
(MURPHY ET AL., 2021)	Empirical and methodological	complex adaptive systems, environmental management	Participatory modelling	ecosystem	Alaska (USA)	No	constraints, catch regulations, social tipping point, limits to change	resources, ecosystem services	No	6: Bounds	2: Stability edges 5: Contours
(BAGGIO ET AL., 2016)	Methodological	institutional economics	Cross-analysis, comparison of CS	local community	69 CS, location not specified	No	social boundaries; biophysical boundaries	common pool resources	Yes	6: Bounds	5: Contours
(NAUGHTON-TREVES, 1999)	Empirical	anthropology, history	Comprehensive or historical analysis	local community	Toro district (Uganda)	No	property rights, park boundaries	fauna, habitats, forests	Yes	6: Bounds	5: Contours
(OSTROM AND NAGENDRA, 2006)	Empirical	institutional economics, political science	Cross-analysis, comparison of CS	local community	South Asia, Africa, USA	No	institutional arrangements, property system, land tenure, boundaries of protected areas	resources	Yes	6: Bounds	5: Contours

(PITTOCK, 2019)	Empirical	political science	Comprehensive or historical analysis	regional	Murray-Darling Basin (Australia)	No	sustainable diversion limits, limits to growth	water resources	Yes	6: Bounds	1: Natural limits
(ERISMAN ET AL., 2013)	Synthesis	environmental science	Review	multiscale	NA	No	limit values, threshold value, excess, overload	ecosystems	No	7: Benchmark values	1: Natural limits
(SCHLEUSSNER ET AL., 2016)	Synthesis	environmental science	Modelling	global, planetary	NA	No	policy targets, nitrogen or phosphorous limitations, temperature limits, absolute thresholds,	climate system, ecosystems, water, crop yields, coral reef	Yes	7: Benchmark values	
(KOCH, 2020)	Theoretical	degrowth	Comprehensive or historical analysis	global, planetary	NA	Yes	planetary boundaries, social limits, open up a space for freedom	resources	Yes	8: Welfare minimums	9: Self-limitation
(BRAND ET AL., 2021)	Position paper	degrowth	NA	global, planetary	NA	Yes	societal boundaries, self-limitation	Natural commons	Yes	9: Self-limitation	8: Welfare minimums 10: Limits of limits
(BAKKER, 2010)	Theoretical	Political ecology, cultural geography	Review	global, planetary	NA	No	limits to nature's neoliberalization; limitations of conceptual frameworks	coproduced socio-nature / neoliberal natures	Yes	10: Limits of limits	
(COTE AND NIGHTINGALE, 2012)	Position paper	Political ecology, nature-society geography	NA	multiscale	NA	No	threshold effects, limits to adaptation, limits of scientific knowledge	ecological dynamics	No	10: Limits of limits	
(INGOLD, 2008)	Position paper	anthropology of nature, philosophy of perception	NA	organisms, life	NA	No	boundaries of exclusion, enclose	continuity of nature, textured world, life, organisms	No	10: Limits of limits	

(REISMAN AND FAIRBAIRN, 2020)	Theoretical	Political ecology, critical agrarian studies	Comprehensive or historical analysis	global, planetary	NA	No	biophysical constraints, obstacles to capitalist agriculture, inseparability of people from their environments	soils, plants and other organisms, unruly biological processes, more-than-human world	No	10: Limits of limits	1: Natural limits

Appendix 2: List of the 30 articles coded in the meta-ethnography and some of their attributes

Abbreviations: CS : Case study ; NA : Not Applicable ; recom. : recommendation

Precisions on column names:

- 6. Theorization: The article includes a section that explicitly theorize on limits or related concepts (Yes or No)
- 8. Nature as…: The view of nature that the article adopts.
- 9. Recom. for action: The article includes some operational recommendations or perspectives for action (Yes or no)
- 10. Main category of limits: The theoretical construct (see table 1 in the main text) that is the most frequently encountered in the article.
- 11. Other categories of limits: Other theoretical constructs encountered in the article.

Appendix 3 – Full description of theoretical constructs on limits

1. Natural limits

Different statements refer to limits as constraints on the expansion or functioning of socio-economic systems. Such limits are physical or biological in nature - either conceived as 'limiting factors' (e.g., the amount of nitrogen in soils or groundwater levels (Dearing et al., 2019; Erisman et al., 2013)) or 'limiting processes' (maintenance and reproduction of ecosystems, (Madrid, Cabello, & Giampietro, 2013)). These types of limits exist in a natural world that is considered to be absolutely finite (in terms of resource stocks), or absolutely limited in terms of rates of production and reproduction of ecosystems. They generally refer to scientific knowledge and 'common sense' (Pittock, 2019), as a maximum amount of resource extraction or exploitation of nature that can be known and quantified, or simply postulated.

This conception of limits is the closest to the 'limits to growth' paradigm (Meadows, Meadows, Randers, & Behrens, 1972), from which articles retain an 'embeddedness' and 'dependency' rationale: the economy depends on the functioning of social organizations, which in turn depend on the functioning of biological and physical systems. When this relationship breaks down due to overexploitation, societies enter a 'dark age' (Costanza et al., 2007). Thus, this corpus examines the capacity of nature to support human needs, or more explicitly, the provision of resources or services necessary for thriving societies. It is not only the quantity and availability of these resources and services that matters, but also their accessibility and integrity to ensure social 'must haves' such as: food production (Cumming et al., 2014; Dearing et al., 2019), prosperity and security (Folke et al., 2002), the sustainability of a society's metabolic pattern or, in a more critical understanding, 'the Western way of life' (Koch, 2020).

Interestingly, the vision of the finiteness of nature coexists with the idea that resources and ecosystem services are socially constructed through technologies and infrastructure, knowledge or social demand. For example, Cumming et al. (2014) explain how changes in demand for ecosystem services due to urbanization lead to problems of overexploitation ('the green loop to red loop transition'). Madrid et al. (2013), in turn, explain that setting a quantitative limit on resource exploitation, in their case water use, depends on the state of knowledge and the state of values. Humans can overcome certain limits (e.g., by removing restrictions on resource accessibility) or exacerbate them (e.g., by overexploiting or degrading resources and processes). In this perspective, limits are given by biological and physical determinisms, but their quantification is contextual (knowledge, technologies), and their integration into human laws depends largely on societal values and power relations.

<u>Remarkable verbatims</u>

- These systems are intimately linked: humanity depends on services of ecosystems for its wealth and security. Moreover, humans can transform ecosystems into more or less desirable conditions. Humanity receives many ecosystem services, such as clean water and air, food production, fuel, and others. Yet human action can render ecosystems unable to provide these services, with consequences for human livelihoods, vulnerability, and security. (Folke, 2022).
- Nitrogen is commonly a limiting factor for the production of food. Humankind has sought

different ways to increase crop production to provide food to sustain a growing population. This has led to the development of synthetic fertilizer production based on the Haber–Bosch process [3,4]. Nitrogen currently provides many benefits to society, in particular to agriculture and industry [5]. (Erisman et al., 2013)

- "While it might seem like common sense that the amount of water that can be extracted is finite, recognition of the limits to growth was first evident in the decision of the state and federal governments to cap surface water entitlements at 1994 levels (Connell, 2007). (Pittock, 2019)

- The loss of a crucial proportion of Earth's fauna during the next 50–100 years would be irreparable over the time frame of human existence, and future societies may struggle to live sustainably if left with unstable, depauperate life-support systems. (Cumming, 2014)

2. Stability edges

Several articles use a concept of limits as the edge of a stability domain ('basin of attraction'), within which the functional integrity of a system is maintained. Beyond the limit of this stability domain, the system switches to another basin of attraction, implying profound transformations (a 'regime shift' or 'state shift') and a loss of the original functional integrity (Cumming et al. 2014)). The limit does not indicate that one basin is more desirable than another, but rather that two fundamentally different system states and operating modes are possible, with difficulties in switching back from one to the other (quasi-irreversibility). The limit here is not fixed a priori - because the landscape of the different basins of attraction and their separations can evolve, for example, due to management decisions - nor is it a measurable quantity. It is part of a heuristic for the dynamics of the social-ecological system.

Edges of a stability domain are the most common category of limits in our meta-ethnography, as other categories (preventive boundaries, thresholds...) rely on them as a theoretical background. It is part of a larger ontology for ecosystems, which recognizes the existence of multiple equilibria (basins of attraction) and transient behavior (Holling 1973). It is then extended to social-ecological systems, a metaphor that emphasizes the irreducible couplings between nature and society and their mutual interactions (Berkes, Folke, and Colding 1998; Liu et al. 2007). This ontology of social-ecological couplings and multiple dynamic equilibria is often referred to as the 'resilience perspective' (Folke 2006), and is based on complex adaptive systems theory (Levin 1998). The underlying explanation can be schematized as follows: couplings between system components generate nonlinear interactions (cause-effect relationships are nonproportional and nonadditive); therefore, the trajectory of a system is path-dependent (the past trajectory of a system determines its future behavior); therefore, multiple states (basins of attraction) can coexist and the transition from one to another is not simple, but possible under significant perturbations in external conditions (Folke 2006; Liu et al. 2007) or internal changes in the system (Horan et al. 2011, parameter shift).

If the type of limit described here always implies a state or regime shift when crossed, slight differences in the content of this shift can be observed, often due to the disciplinary background of the authors. The biotic dimension of shifts can be emphasized: the change of state may imply new species compositions and thus new ecosystem processes, functions and services (Barnosky et al. 2012; Folke 2006; Turner 2010). The social-ecological couplings may also be the object of the shift: authors then emphasize new types of interactions between technologies, human demography and ecosystems (Cumming et al. 2014) or changes in the organization and resources of a community (Liu et al. 2007;

Martin 2015). Finally, the notion of state or regime shifts can be applied to sociopolitical transformations - fundamentally new urban systems (Osman 2021) or the restructuring of institutional arrangements (Young 2010).

Furthermore, if the theory of qualitative shifts is originally based on ecosystem ecology and local empirical examples (clear to turbid lakes, changes in forest species composition...), the question of cross-scale effects and the relevance of such a theory at the global scale arises (Barnosky et al. 2012; Folke 2006; Folke et al. 2011; Liu et al. 2007). This question lends pejorative and catastrophic overtones to the notion of regime shift (cf. 'critical threshold values'). Similarly, evidence of 'surprise' (when management decisions produce unintended shift effects because the complexity of social-ecological systems is not well understood, Liu et al. 2017) is consistent with such a precautionary approach (Folke et al. 2006, Murphy et al., 2021). In most cases, however, change is seen as both a threat and an opportunity, a distinction sometimes embedded in the terminology of resilience vs. adaptability vs. transformability (Walker et al. 2004).

Resilience ('the capacity to buffer change, learn, and develop' (Folke et al. 2002)) is sought when the goal is to remain within a known domain of stability, and, at the other edge, transformability ('the capacity to create untried beginnings from which to evolve a new way of living when existing ecological, economic, and social conditions make the current system untenable' (Folke et al. 2011)) is sought when the goal is to drive or navigate change toward a new domain of stability. As resilience is alternatively treated as a system property or as a coping strategy (Olsson et al. 2015), the corpus is accordingly divided between articles that adopt a strictly descriptive-analytical view and those that include recommendations for action (e.g. adaptive management, flexibility, navigating change, monitoring and informing early signals of shifts).

<u>Remarkable verbatims:</u>

- Couplings between human and natural systems vary across space, time, and organizational units. They also exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises. (...)These studies have offered unique interdisciplinary insights into complexities that cannot be gained from ecological or social research alone. (Liu et al., 2007)

- The resilience perspective shifts policies from those that aspire to control change in systems assumed to be stable, to managing the capacity of social–ecological systems to cope with, adapt to, and shape change (Berkes et al., 2003, Smit and Wandel, 2006). (Folke, 2006)

- But resilience is not only about being persistent or robust to disturbance. It is also about the opportunities that disturbance opens up in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories. (Folke, 2006)

- Disturbance may accelerate changes in species composition or even biome boundaries (Frelich and Reich 2009), and potentially hasten transitions to ''no-analogue communities'' (Williams and Jackson 2007). [...] If large-scale changes in biotic communities occur after disturbances, there will also be significant consequences for many ecosystem processes. (Turner, 2010)

- It is now well documented that biological systems on many scales can shift rapidly from an existing state to a radically different state. Biological 'states' are neither steady nor in equilibrium; rather, they are characterized by a defined range of deviations from a mean condition over a prescribed period of time. The shift from one state to another can be caused by either a 'threshold' or 'sledgehammer' effect. [...] In both cases, the state shift is relatively abrupt and leads to new mean conditions outside the range of fluctuation evident in the previous state. (Barnosky et al., 2012)

- Once a tipping point is reached, seemingly entrenched arrangements can come down like a house of cards. The resultant crises are not necessarily bad; they can provide opportunities for making needed adjustments in institutional arrangements that are simply out of the question during normal times. (Young, 2010)

- The shift from a green to a red loop represents a fundamental change in system functioning that requires two different system models, rather than parameter changes within a single model. (Cumming et al., 2014)

- The households of Anaktuvuk Pass have demonstrated resilience in the sense that they incorporated new resources to maintain Rangifer harvest while increasing material well-being. (...) Households have taken advantage of the opportunities that came from rapid change to manage vulnerability and risk. (Martin, 2015)

3. Critical threshold values

In a number of statements, limits are tipping points for the biosphere or System Earth, understood as a life-supporting system, and in particular as a system that supports humanity. Limits are a maximum level of a key variable of this system that, when crossed, causes a critical system shift. Such a shift is critical in the sense that it has catastrophic consequences: not only a threat to human livelihoods and societal development (Folke, 2006a), but also, more broadly, to the current biota that took its place and evolved under the stable conditions of the Holocene (Barnosky et al., 2012; Rockström et al., 2009).

Boundaries are part of a description of biogeophysical phenomena, deciphered by scientists through observation and modeling of social-ecological interactions. In this corpus, human preferences have no influence on limits, as they exist as natural laws: 'The thresholds in key Earth system processes exist independently of human preferences, values or trade-offs', (Rockström et al., 2009). However, human societies have a responsibility to better understand (and quantify if possible) these natural threshold values and to avoid crossing them. Indeed, a common denominator is that the authors point to human societies not only as victims, but also as drivers of recent and future biogeophysical changes.

The articles (in whole or in part) found in this corpus share a common conceptual background - that of resilience thinking, which allows for the consideration of multiple basins of stability and dynamics of collapse in social-ecological systems (Gunderson & Holling, 2002; Walker et al., 2006). However, because of the unprecedented scope and magnitude of the expected collapse(s), there is no question here of considering collapse as a source of opportunity (Folke, 2006b) or creative destruction (Holling, 2001), as the resilience perspective generally suggests. Indeed, the authors who conceptualize limits as critical tipping points for System Earth insist on their global, systemic, and unpredictable significance. They develop the nature of such limits, which can be sharp or fuzzy ('thresholds' or 'sledgehammers' according to Barnosky et al. (2012); 'thresholds' versus 'dangerous levels' for Rockström et al. (2009) - a terminology further refined by Dearing et al. (2014)). In particular, limits become threatening due to escalation mechanisms such as scale jumps (when effects in a local variable propagate and cause a large-scale shift) or positive feedback loops (when a process feeds on itself and its effects demultiply in magnitude).

Concerns about limits are initially methodological-how to detect and quantify them. Barnosky et al. (2012) discuss approaches to tracking planetary transitions and detecting warning signals: capturing direct and indirect forcings, or directly monitoring biological changes at local scales. Dearing et al. (2019) can be seen as an application of the latter, in the case of soil, river and lake systems in a Chinese region (Shucheng). Rockström et al. (2009) have provided a working definition of 'control variables' (aggregative, synthetic, measurable) that allow the selection of processes to be monitored and managed as a priority. The same is true for Erisman et al. (2013), who aim at strategically targeting actions towards the disruption of the nitrogen cycle. In all these papers, monitoring methods and policy actions are intertwined within an anticipatory logic: information and detection are expected to generate anticipatory actions and preventive public policies and attitudes (see Preventive boundaries).

Remarkable verbatims:

- The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. (Barnosky et al., 2012)

- In view of potential impacts on humanity, a key need in biological forecasting is the development of ways to anticipate a global critical transition, ideally in time to do something about it. (Barnosky et al., 2012)

- Water quality has deteriorated most rapidly and there is evidence that critical thresholds may have been passed in downstream lake ecosystems. (Dearing et al., 2019)

- Here, we distinguish between identifiable planetary thresholds driven by systemic global scale processes (impacting subsystems "top down") and thresholds that may arise at the local and regional scales, which become a global concern at the aggregate level (if occurring in multiple locations simultaneously) or where the gradual aggregate impacts may increase the likelihood of crossing planetary thresholds in other Earth System processes (thus affecting the Earth System "bottom-up"). (Rockström et al., 2009)

4. Preventive boundaries

In a number of articles, limits are considered as 'boundaries' in the key processes of social-ecological systems, i.e. values of control variables that indicate the approach of states or thresholds that threaten the stability of the social-ecological system and thus human well-being. They are not the critical values that, when exceeded, trigger a system shift, because the limits are at a 'safe distance' from these critical values. They are not associated with regulations, let alone enforcement systems, but simply express a caution: they are warnings, at best early warnings.

Boundaries are normative in nature: they are upper limits that should not be exceeded because of the risks involved. Their definition involves value-laden decisions, in particular the choice of 'safe' distances from (uncertain) dangerous values, which depend on risk aversion. The definition of boundaries is in itself a committed practice: it presupposes that system stability is a desirable property, and that warnings can help to promote sustainable management of socio-ecological systems.

This notion of 'boundaries' stems from the seminal paper by Rockström et al. (2009): planetary boundaries are defined for nine key Earth System processes, which together delineate a 'safe operating space for humanity'. The premise is that human societies depend on stable (Holocene) environmental conditions to thrive, while the Earth System is currently at risk of abrupt global environmental change. In fact, the authors estimate that human activities have already caused several planetary boundaries to be crossed, threatening overall stability. The threat to stability is exacerbated by the fact that ''transgressing one boundary can [...] seriously threaten the ability to remain within safe levels for other boundaries.'' Dearing et al. (2014) argue for a multiscale approach in which boundaries should also be defined at regional scales, as threats to the sustainability of regional socio-ecological systems and local livelihoods may arise before they become a concern at the global level, justifying a regional precautionary approach. It is also justified by governance concerns, because natural resource management and socio-economic policies are primarily defined and implemented at regional and national scales.

Other scholars recognize the need for early warning systems (e.g., Barnosky, 2012) to avoid critical transitions; however, some other articles (Young, 2010, Pittock, 2019) show that warnings are not sufficient to trigger the adoption of appropriate regulatory limits or institutional adaptations. An example is provided by Pittock (2019) for the Murray-Darling Basin: despite the recognized limit of water availability and the expected exacerbation of water scarcity due to climate change, water regulations are in practice disconnected from precautionary levels; among other factors, uncertainty about the level of the limit and technological innovations serve as arguments for setting less stringent rules. Brand et al. (2021) provide a more fundamental critique of the boundary approach. They claim that the approach fails to address 'the dominant economic and political logics, power relations, and underlying interest structures as the main societal causes of boundaries being transgressed.' More than early warnings, it is the ways in which capitalism and democracy operate that need to be brought to the fore if we are to address sustainability issues.

Remarkable verbatims:

- The Anthropocene raises a new question: "What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales?" (Rockström et al. 2009)

- The proposed concept of "planetary boundaries" lays the groundwork for shifting our approach to governance and management, away from the essentially sectoral analyses of limits to growth aimed at minimizing negative externalities, toward the estimation of the safe space for human development. Planetary boundaries define, as it were, the boundaries of the "planetary playing field" for humanity if we want to be sure of avoiding major human-induced environmental change on a global scale. (Rockström et al. 2009)

- There are, as far as we have determined in this proof-of-concept paper, nine planetary boundaries. On condition that these are not transgressed for too long, humanity appears to have freedom to maneuver in the pursuit of long-term social and economic development within the stability domain provided by the observed resilience of the Earth System in the Holocene. (Rockström et al. 2009)

- Because critical transitions can occur at any scale (Scheffer et al., 2001; Folke et al., 2004; Lenton, 2013), the original planetary boundaries framework recognized that the effects of crossing multiple thresholds at regional scales can aggregate to become a global concern (Rockström et al., 2009a,b). But the cascading effects of environmental degradation (Peters et al., 2011) can have critical consequences for the sustainability of regional systems themselves, well before the effects are obvious at the global scale. This means that global sustainability requires both regional and planetary dimensions to be addressed. (Dearing et al., 2014)

- Naturally, early warning is not sufficient to avoid or mitigate stress; there are numerous examples of regimes that turn out to be incapable of adjusting to severe stresses even when the existence of growing threats becomes common knowledge. (Young, 2010)

- Examining planetary boundaries from this perspective changes the scope of the social-ecological transformations needed to remain in a metabolic “safe space.” It underlines the strategic need to take into account the dynamics and variability of the capitalist mode of production, reproduction, and living, as well as its social power relations and social inequalities within and across societies. (Brand et al., 2021)

5. Functional contours

Many articles in our corpus (Baggio et al., 2016; Cumming, Cumming, & Redman, 2006; Madrid, Cabello, & Giampietro, 2013; Murphy et al., 2021; Naughton-Treves, 1999; E. Ostrom & Nagendra, 2006; Young, 2010) introduce the notion of limits as a contour or delimitation, with the underlying question of whether this limit is appropriate for the issues at hand. In this corpus, limits circumscribe a system or subsystem, a phenomenon, an issue or an 'action situation' (sensu Elinor Ostrom, 2009), and in doing so enable and constrain the emergence and effectiveness of collective actions, policies or organizations. Most authors refer to a social-ecological systems perspective, observing a functional relationship between social systems and ecosystems. This perspective of limits as outlines/contours/delimitations allows authors to ask (1) whether human communities have sufficient control over their environment, and (2) how the multiscalar dimension of social-ecological systems can be adequately taken into account - methodologically and in the practice of governance.

The most important theoretical contribution to defining matches and mismatches in the functioning of social-ecological systems is that of Cumming, Cumming, & Redman (2006). They refer to ‘scale mismatches’ as a situation in which 'the scale of environmental variation and the scale of social organization in which responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost.' The authors distinguish three types of scale mismatches: temporal, spatial, and functional. In line with this match/mismatch view is the idea of successful configuration settings for the governance of common pool resources (Baggio et al, 2016). For example, Baggio et al. (2016) show that clearly defined social boundaries (qualifying people as rights holders) are a success factor when the managed natural infrastructure/resource is mobile (e.g., tuna fish).

The unintended consequences of regulatory delimitations that are not adapted to ecosystem realities is a fundamental issue raised by various empirical works. Martin (2015) shows that the delimitation of rights and beneficiaries over caribou harvesting on the one hand increased control over the resource at one scale (that of the nation-state), but on the other hand deprived local communities of their main source of subsistence. Ostrom & Nagendra (2006) and Naughton-Treves (1999), in two very different contexts, show that conservation policies based on simple spatial delimitations such as parks can have perverse effects and recommend more complex institutional arrangements that allow for better recognition of wildlife mobility and cross-scale linkages (Berkes, 2002). Similarly, albeit in a prospective manner, Murphy et al. (2021) map the multiple pathways through which the introduction of a narrowly defined ‘prohibited species catch’ limit in Alaska's commercial fisheries can affect other components of the social-ecological system, particularly the mortality of other species and the organization and safety of fleet crews.

The causes of inadequacy are another focus for authors adopting a coevolutionary perspective: how is it possible for coevolutionary dynamics to fail to provide appropriate delineations between social and ecological systems? Cumming et al. (2006) suggest as answers changes in the scale of environmental variation, management organization, or both social and ecological interactions. Young (2010) and Koch (2020) elaborate on socio-political lock-ins that impede adaptive mechanisms in the face of changing conditions (e.g., 'institutional arthritis' and 'habitus' respectively), while Dearing et al. (2019) highlight the role of cognitive biases (e.g., 'creeping normalcy') borrowed from Jared Diamond (2005) to explain how gradual changes such as the erosion of farmland fertility, even when noticed by protagonists, do not easily provoke changes in routines and practices.

Finally, methodological considerations also revolve around the understanding of limits as contours, outlines or delimitations. Madrid, Cabello & Giampietro (2013) use a metabolic approach to assess the coherence of patterns and structures in social-ecological systems. For them, as defined in the Musiasem framework (Giampietro, Mayumi, & Ramos-Martin, 2009), coherence is a factor of sustainability and must be found at two different levels: between the rate of resource flows and desired societal functions, and between the structural and functional characteristics of a society and the constraints of the ecosystems that support it. Water resources, for example, constitute, on the one hand, a socio-technical supply system that responds to a social demand for water and, on the other hand, an ecological substrate for various ecosystems on which human societies depend. This perspective extends the question of fit and coherence to a variety of non-equivalent framings and thus scales.

Remarkable verbatims:

- Scale mismatches occur when the scale of environmental variation and the scale of social organization in which the responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost. (Cumming and Cumming, 2006)

- However, the mechanisms and processes involved in the expression of their respective metabolic patterns are operating at different scales. Therefore, it is impossible to perceive and represent in quantitative terms the process of the self-organization of SESs using a single scale and a single quantitative approach. (Madrid et al, 2013)

- Necessary reform in property rights is constrained by historically rooted political and physical conditions, and idealized notions of 'local community'. Neither wildlife nor the rural poor are served by simplistic prescriptions to 'hand over' wildlife to imagined communities isolated from government or market forces. Instead, wildlife property arrangements must reflect ecosystem-level processes and macropolitical and economic forces shaping local use of wildlife. (…) Considerable financial and political support is required to build comanagement systems allowing local communities and the government to negotiate and experiment with alternative ways of owning and using wildlife beyond park boundaries. (Naughton-Treves and al., 1999)

- It is difficult to forecast how fishery policies will affect commercial fishers amidst evolving conditions and in complex social-ecological systems with imprecise boundaries. (Murphy et al. 2021)

6. Institutional bounds

A series of coded statements refer to limits in social-ecological systems in terms of how and to what extent people use (hunt, protect, withdraw...) natural resources. In this approach, the limit is socially constructed by rules and regulations, the limit being what various institutions define and set (either by force, internal habits or beliefs, or through processes of collective choice...) as acceptable behavior. These limits aim to ensure the conservation of animal populations, forests, water, and/or to mitigate conflicts between humans and wildlife or between human users. The articles contributing the this limit category follow a case study approach, with in-depth case studies or comparative case studies, and use extensive empirical work (observation, interviews, document collection). In contrast to other approaches to social-ecological systems, the authors essentially perceive nature as a resource, often as a resource system that is more complex than a simple stock, but without investigating its ecological or hydrological functioning in depth.

We treat these systems of rules as types of limits because of their function, not because of their nature: they bind people together, moderate or constrain social-ecological interaction. They take place within complex institutional arrangements that are historically constructed, negotiated, and sometimes contested. The historical trajectory of these complex institutional arrangements depends primarily on the persistence (or change) of the user community, the ongoing enforcement (or delegitimation) of the rule, and the value attached to the resource at stake.

Naughton-Treves (1999) provides a detailed account of the historical development of the system of regulation of elephant populations in Toro District (Uganda) during the 20th century. In particular, he examines how the complex interplay of the Toro kingdom with colonial institutions changed the allocation of property rights from the spirits and the king to conservation parks and licensed gun owners. The development of institutional bounds is sometimes observed as a result of controversies (Frolov 2022), for example, "limits to growth" vs. "pioneer myth" for Australian water regulations (Pittock 2019), which pushes them forward or backward.

The authors' interest is not in describing these institutional bounds per se, but in understanding the conditions and trajectories of their emergence or definition, their application (means, settings, adaptive capacity), and their effectiveness with respect to specific objectives, generally the long-term preservation of the resource. The authors' contributions are primarily located on the governance side of social-ecological systems. Pittock's article (2019) illustrates a concern for emergence and reform mechanisms by highlighting the key role of environmental crises (droughts, floods, algal blooms) in triggering 'sustainable diversion limits', for example reactive rather than proactive limits. The question of effectiveness cuts across the articles that fall in this category and is often linked to questions of legitimacy and empowerment: is the limit the result of collective action or is it imposed on resource users?

While Naughton-Treves (1999) offers recommendations for overcoming current community conflicts and the collapse of elephant populations through co-management involving local communities, indigenous people, migrants, and the state, Ostrom and Nagendra (2006) tend to derive more general governance principles for combating deforestation from the commonalities found in the case studies.

This effort follows the logic of design principles for common pool resource management (Cox, Arnold, and Tomás 2010; Ostrom 1990).

<u>Remarkable verbatims:</u>

- The temptations to overharvest from natural resources are always large. If the formal rules limiting access and harvest levels are not known or considered legitimate by local resource users, substantial investment in fences and official guards to patrol boundaries are needed to prevent ''illegal'' harvesting. (...) When users are genuinely engaged in decisions regarding rules that affect their use, the likelihood of users following the rules and monitoring others is much greater than when an authority simply imposes rules on users. (Ostrom et Nagendra, 2006).

- In the debates on federation of Australia the management of the Basin was one of the most contentious issues (Connell, 2007). (...) The history of water management reforms in the Basin has been driven by crises – droughts, floods and cyanobacteria blooms – only for these programs to be ignored or undermined in subsequent good years (Connell, 2007). This poor approach to risk for drought management has been termed the 'hydro-illogical cycle' (Wilhite, 2011). While cyclical crises are a driver of reactive policy reform, can Australia do better? (Pittock, 2019)

- During the early colonial period then, great emphasis was placed on controlling and confining wildlife to parks. Several species were subject to control operations, but none received more attention than elephants. Elephant control campaigns were particularly intense in Toro where they legitimized the king's exclusive claims to ivory, and shaped settlers' attitudes to wildlife. (Naughton-Treves, 1999)

7. Benchmark values

We coded statements from three articles (Dearing et al. 2014; Erisman et al. 2013; Schleussner et al. 2016) based on environmental science that refer to limits as benchmark or normative values that qualify the state of the environment (climate, water quality, nutrient loads, etc.). These limit values serve both the activities of assessment (providing references for comparisons - e.g., better/worse than) and valuation (making value judgments - e.g., good/bad for health or the environment) (Frame and O'Connor 2011). There is no explicit link between these thresholds and the risk of a socio-ecological shift, as is the case with preventive thresholds such as planetary boundaries; however, knowledge of ecological, geological or physiological processes is the scientific basis used to legitimize the benchmarks.

The function of benchmark values is not to restrict, but to set goals or inform about human and ecosystem health (Erisman, 2014). We consider these benchmarks as limits because they define an acceptable maximum level or range for an indicator of interest. The coded articles focus on the effects of chemical concentrations such as N2 on ecosystems or human health (Erisman et al., 2013) and temperature targets such as those included in the so-called Paris Agreement of 2015 - the international treaty on climate change (Schleussner et al., 2016).

Dearing et al. (2014) state that the way in which a benchmark is defined is based on "scientific, expert or public opinion, through negotiation and compromise". While these limits are not defined arbitrarily because they rely on scientific and expert judgment, optimality or scientific robustness is not guaranteed. The process of setting the benchmark is rarely scrutinized as something outside the scope of the articles reviewed, although controversies about the "right level" can be raised. Indeed, in the case of climate change, Schleussner et al. (2016) point out that the 2°C warming target has not been identified by scientists as a safe limit, but actually assumes significant risks and degradation of the environment (extreme weather events, changes in water table availability, crop yield projections, sea level rise, and coral reef degradation) (Schleussner et al., 2016). Knutti et al. (2016) show that the 2°C target is a political consensus that takes into account what policymakers consider to be both realistically achievable and tolerable. The need for policymakers to set and demonstrate targets for environmental improvements also plays a key role in the development and dissemination of benchmark limits. The degree of institutionalization varies, but many benchmarks - and thus "norms" - are promoted or enforced by official organizations such as the World Health Organization (Erisman et al. 2013) or the European Union (Dearing et al. 2014).

Because these benchmarks and norms are based in part on scientific evidence, they straddle the line between scientific assessment and political orientation, even as policymakers seek to make science-based decisions. In most cases, the authors clearly assume that the limits they use refer to what is collectively (including scientists, experts, policy makers, public opinion) considered acceptable (Schleussner et al., 2016; Erisman et al., 2013).

Remarkable verbatims:

- Type I boundaries refer to linear trending data, where a regional regulatory limit on a particular ecosystem process is set by scientific, expert or public opinion, through negotiation and tradeoffs between the benefits and damages arising from particular activities. This type of boundary is commonly used for management of degraded landscapes and ecosystems (e.g. quality targets, critical loads), but it is only weakly linked to system dynamical properties and generally assumes stationarity in the trend (Dearing et al.2014).

- Figure 2 is a first attempt by expert judgement to describe the major consequences of human induced Nr environment as synthesized in this paper (Erisman et al. 2013)

- The assessment of levels of dangerous interference is primarily a political process that requires value judgements and depends on different world views. Schleussner et al. (2016)

- The current 2 °C UNFCCC target is a compromise between what is deemed possible and desirable, rather than a “planetary boundary” that clearly separates a ‘safe’ from a ‘dangerous’ world. (Knutti et al. 2016)

- The choice of any target is ultimately a compromise between costs, benefits, trade-offs, and risks, where scientific evidence is combined with moral and ethical arguments — much like agreeing on a single speed limit on all roads. (Knutti et al. 2016)

8. Welfare minimums

Some articles in our corpus refer to minimum limits in welfare indicators, “below which lie shortfalls in wellbeing, such as hunger, ill health, illiteracy, and energy poverty” (Raworth 2017 for the general conceptualization, Dearing et al. 2014 as an application, Brand et al. 2021 for a critical perspective). These limits are univocally called “social boundaries”. Social boundaries do not exist independently of planetary boundaries (Rockström et al. 2009, see PREV), and they define together not only a safe but also just operating space for humanity, often referred to as “SJOS” (Dearing et al. 2014; Raworth 2012). The articles explicitly rely on the doughnut economics introduced by Raworth, explaining the homogeneity of defiitions. For coherence, we added to our corpus the original Oxfam paper (Raworth 2012), which was not included in our database due to its non-academic status.

The justice criterion, the keystone of the social boundary rationale, emerges in a context where international agreements to reduce the human footprint on the environment are being contested by developing countries and human development NGOs (Biermann et Kim 2020; Raworth 2012). Social boundaries - here called 'welfare minimums'- embed an explicit claim for modulating efforts according to responsibilities and allocating non-renewable resources according to needs: “Social justice demands that this double objective [of reducing resource use and eradicating poverty] be achieved through far greater global equity in the use of natural resources, with the greatest reductions coming from the world’s richest consumers.” (Raworth 2012)

Welfare minima thus correspond to quantitative targets based on international norms that ensure the absence of basic human rights deprivations. This content contrasts with planetary boundaries based on biophysical knowledge (see Preventive Boundaries) and self-imposed limits set through collective deliberation (see Self-limitation). In the original framework (Raworth 2012), as in the other applications we found, the targets are 11 and relate to the most consensual government priorities for the Rio+20 United Nations Conference: food security, income, water and sanitation, health care, education, energy, gender equality, social equity, voice, employment, and resilience. Ideally, these goals are expected to guide new perspectives on sustainable and inclusive development, particularly in contrast to economic growth, which is underpinned by the broad use of GDP (Raworth 2012). They are also expected to help set internationally agreed targets, although operationally, national and regional scales are considered to be where assessments have the greatest policy impact (Dearing et al. 2014). When used to derive policy recommendations, authors use welfare minima and the doughnut as a "compass" (Raworth 2017) or "barometer" (Dearing et al. 2014) rather than a strict assessment framework.

Although there is no explicit upper limit to the social boundaries of Raworth (2012), there is an implicit limit created by biophysical boundaries (Brand et al. 2021). Indeed, the treatment of biophysical issues in the doughnut is more focused on resource use than on biophysical processes and thresholds, as the focus is on how to allocate fragile and limited resources to ensure good living conditions for all (Raworth 2012). Because their rationale is different (international norms vs. scientific knowledge; resource allocation vs. destabilization risks), we have chosen a vocabulary ("welfare minima") that is not directly symmetric to that of preventive boundaries.

Moreover, the joint use of the terms "environmental ceiling" and "social foundations" draws attention to the balance between the two types of objectives, and thus treats trade-offs between welfare and environmental protection rather than their interdependence and synergies. Operationalizations of the doughnut framework are keen to highlight such trade-offs. For example, Dearing et al. (2014) show that agricultural intensification has maintained food security but degraded ecological processes (water quality and regulation) in the Erhai Lake catchment. Similarly, using data from 150 countries, O'Neill et al. (2018) show that no country is able to simultaneously respect planetary boundaries and social foundations.

Remarkable verbatims:

- The social foundation forms an inner boundary, below which are many dimensions of human deprivation. The environmental ceiling forms an outer boundary, beyond which are many dimensions of environmental degradation. Between the two boundaries lies an area – shaped like a doughnut – which represents an environmentally safe and socially just space for humanity to thrive in. It is also the space in which inclusive and sustainable economic development takes place. (Raworth 2012)

- In direct contrast to environmental ceilings, social foundations are not defined by social dynamics but by nationally or internationally agreed minimum standards for human outcomes (Raworth, 2012). While some social standards have been established at the global scale, such as through the Universal Declaration of Human Rights and subsequent human rights law, their governance is enforced at the regional/national level with supranational governance continuing to be the exception for the foreseeable future. Therefore to have most policy impact, our framework must be applicable to regional governance systems, their practicalities and motivations. (Dearing et al. 2014)

- Until these opportunities [for methodological improvements] are realized, the RSJOS [Regional Safe and Just Operating Space] images presented are essentially informative, teleological devices providing a regional barometer of sustainable development for policy traction and strategic scientific studies. (Dearing et al. 2014)

9. Self-limitation

This category of limits is mainly represented in the articles by Brand et al. (2021) and Koch (2020) and is colored by a degrowth and relational perspective on human-nature interactions. Although grounded in the same will to critique and extend the planetary boundaries framework of Rockström et al. (2009) as the social boundaries concept, the statements coded in this category retain their uniqueness in assuming a resource abundant (but not unlimited) planet compromised by specific production and consumption dynamics.

The meaning of limits is a fundamental concern, with the related question of the process of setting them. The meaning is that of self-limitation, in close relation to a critique of the capitalist economy - with wealth defined as the accumulation of commodities, asymmetrical and discriminatory social relations for production and consumption, deregulated labor and financial markets, among other features.

For Brand et al. (2021), self-limitation is seen as a condition for collective and individual autonomy and vice versa, while capitalism produces heteronomy and exploitative relations. These authors refer to the philosophy of Gorz (Gorz, 1980): "Within societal boundaries and through collective self-limitation, the conditions to live a good life neither come at the expense of others' ability to do the same, nor of the flourishing of future generations or non-human others" (Brand et al., 2021). The function of the limits described here is to secure universal human (and non-human) needs, sensu Max-Neef, Elizalde, & Hopenhayn, (1992), including freedom, participation, and identity. A list of possible subjects for which self-limitations apply is given: "poverty, inequality, ecological destruction, injustices, subordination, exploitation, consumption, defense of the commons, and so forth," although these are open to adaptation. Their level (especially the upper level, in contrast to the notion of social foundations of Raworth, (2012)) is subject to debate and contestation. Limits are somehow the expression of a social contract, extended to non-humans and future generations, achieved through collective deliberation. Humans in society have agreed to set collective limits in exchange for securing collective freedom and as a way to live individually good and autonomous lives. In line with the idea of the politics of sobriety (Villalba, 2023), the setting of limits is a creative and polymorphic process that drives and relies on multiple philosophies and social experiments (Buenvivir, Kametsa Asaike, Ubuntu...).

Koch (2020) places his reflection upstream of the ambition of collectively set limits. For him, the main issue is to succeed in deprioritizing economic growth in the face of social practices that favor, even if unintentionally, the reproduction of the same imaginaries. He borrows Bourdieu's notion of habitus to consider people not as passive but as "capable of making a difference, but always within certain social limits set by the historical period in which they live" (Koch, 2020). For him, we must first create favorable conditions before the degrowth or post-growth alternatives, justified by the multiplication of crises, become audible. To this end, scholars, activists and citizens need to create deliberative forums from which a social "counter-training" could emerge, before asking the question of how and at what level collective limits should be set.

Remarkable verbatims:

- “The central idea of societal boundaries is a change of analytical and political perspectives: rather than thinking of the planet as bounded, we insist to think of the planet as potentially abundant – as long as we limit ourselves collectively and make space for others to share the resources it has to offer in a responsible way among current living and future generations.” (Brand et al., 2021)

- “Shifting the focus from boundaries and limits to self-limitation emphasizes that this is a social challenge and a process rooted in forms of participation, collective self-determination, and democratic deliberation.” (Brand et al., 2021)

- This multidimensional crisis suggests that the Western European postwar class compromise, including its promise of permanent and increasing material prosperity based on the provision of economic growth (Lutz 1989), has come to an end. Yet whether this crisis of the economic and social order will eventually result in an overcoming of the capitalist growth economy via an ecological and social transformation and degrowth is far from certain. (Koch, 2020)

- Researchers could contribute to such citizen forums with, for example, information on the size of ecological footprints that are within sustainable levels, while the whole forum could deliberate on what kind of lifestyles and production patterns this may allow. (Koch, 2020)

10. Limits of limits

Some articles in our corpus, namely Bakker (2010); Brand et al. (2021); Cote & Nightingale (2012); Ingold (2008); Reisman & Fairbairn (2021), support a critical social science perspective (based on political ecology, the degrowth movement, or critical geography) to develop a "limits of limits" argument. They highlight biases of an ontological, conceptual, and methodological nature, whether in the resilience perspective, the planetary boundaries framework, or the Anthropocene concept - all of which address and refer more or less explicitly to the definition of limits in social-ecological systems. For these authors, limits constrain and reduce the understanding of human-nature relations. They adopt different levels of criticism, from revealing a lack of nuance to over-generalization ("It is not economic activities in the abstract that lead to ecological crisis, but rather economic activities with particular logics and under certain circumstances. (Brand et al., 2021)). Finally, some denounce the loss of the sense of inhabiting the world (Ingold, 2008). These articles echo the "critique from science and technology studies" that Biermann & Kim (2020) have already identified with respect to the planetary boundaries framework.

'Limits of Limits' statements embed a reflexive approach to existing concepts, sometimes supporting, extending or revising them, sometimes rejecting them, with both a deconstructive and a proposing move. The deconstructive move revolves primarily around reductionism in diagnosing the ecological crisis, qualifying its causes, or offering solutions. First, the narrow scope of environmental issues considered to define a safe operating space is criticized by Brand et al. (2021). Then, in terms of drivers, the treatment of humanity as a species in the terminologies "Anthropocene" and "coupled human-nature system" is considered problematic by Reisman & Fairbairn (2021) because it masks the unequal contribution of societies to environmental degradation(Reisman & Fairbairn, 2021), Finally, in terms of solutions envisaged, Brand et al. (2021) point to the emergence of a new critical orthodoxy around the political use of planetary boundaries, while Koch (2020) suggests that imaginaries of change remain constrained by habitus, in a cultural and political space that marginalizes degrowth options.

As a consequence of this narrowing, framing biases emerge, namely the reification of nature and the depoliticization of ecological crises. Indeed, for Brand et al. (2021), planetary boundaries offer an "astronaut's eye view" of the Earth that can only be provided by scientists. This critique is further developed by Ingold (2008) from an ontological standpoint: seeing nature as a world external to that of humans suggests that living beings exist prior to individual experience and mutual ties. Depoliticization stems mainly from the consideration of humanity as a single entity, with biological characteristics rather than historical and socio-political legacies, as exemplified by the concept of the Anthropocene (Koch, 2020; Reisman & Fairbairn, 2021). In addition, the use of "abstract criteria" to model institutional factors leading to (un)sustainability precludes a comprehensive understanding of power relations and social-ecological agency (Cote & Nightingale, 2012).

Concerned with unlocking transformative action (except in the case of Ingold, 2008), the authors contributing to the 'limits of limits' perspective take a propositional step that offers ways to overcome the criticisms they address. Rather than specific recommendations, they propose new concepts and ontologies: a comprehensive view of socio-nature, with non-humans understood as political subjects (Bakker, 2010), the expansion of values, worldviews, and legitimate knowledge about limits (Brand et al., 2021), a stronger commitment to empiricism to reveal the heterogeneity and complexity of social-ecological situations, and the plurality of ways to capture, understand, and respond to change (Cote & Nightingale, 2012).

<u>Remarkable verbatims:</u>

- Attributing global change to a universalized human "Anthropos," many critical scholars argue, risks ignoring the fact that some human groups have contributed far more to globally problematic transformations than others. (Reisman & Fairbairn, 2020)

- In each historic transformation, humanity appears as far from a unified force, and domination over Earth systems is far less complete, unidirectional, or assured than it appears at first glance. (Reisman & Fairbairn, 2020)

- Potential barriers or obstacles to transformation already arise in the process of establishing boundaries – and not only when established boundaries are translated into political measures. (Brand et al., 2021)

- The focus of empirical investigations and theoretical development shifts to political and ethical questions as crucial drivers of social-ecological outcomes rather than 'inconvenient' politics that can be simply sorted out through institutional design." (Cote & Nightingale, 2012)

- The open world, however, has no such boundaries, no insides or outsides, only comings and goings. Such productive movements may generate formations, swellings, growths, protuberances, and occurrences, but not objects. (Ingold, 2008)