

Perspective

A Brief Perspective on Environmental Science in the Anthropocene: Recalibrating, Rethinking and Re-Evaluating to Meet the Challenge of Complexity

Farhan R. Khan ^{1,2,*}, Stephanie Storebjerg Croft ^{2,†}, Elisa Escabia Herrando ^{3,†}, Athanasios Kandylas ^{4,†}, Tabea Meyerjuergens ^{5,†}, Dylan Rayner ^{6,†}, Juliane Schulte ^{7,†} and Ingmar Valdemarson á Løgmansbø ^{8,†}

- ¹ Norwegian Research Center (NORCE), Nygårdsporten 112, NO-5008 Bergen, Norway
 - ² Department of Science and Environment, Roskilde University, DK-4000 Roskilde, Denmark; sbcroft@ruc.dk or s.croft.b@gmail.com
 - ³ Department of Medical Biochemistry and Microbiology, Uppsala University, P.O. Box 582, 751 23 Uppsala, Sweden; elisa.escabia@gmail.com
 - ⁴ National Institute of Aquatic Resources (DTU Aqua), Technical University of Denmark (DTU), DK-2800 Kgs. Lyngby, Denmark; kand-2@hotmail.com
 - ⁵ Department of Marine Sciences, University of Gothenburg, P.O. Box 461, SE-405 30 Gothenburg, Sweden; gusmeyerta@student.gu.se
 - ⁶ Department of Agroecology, Aarhus University, P.O. Box 50, 8830 Tjele, Denmark; dln.rayner@gmail.com
 - ⁷ Department of Plant and Environmental Sciences, University of Copenhagen, DK-1871 Frederiksberg, Denmark; schulteju1@gmail.com
 - ⁸ Centre for Science Studies, Aarhus University, DK-8000 Aarhus, Denmark; ingmar93@gmail.com
- * Correspondence: fakh@norceresearch.no or farhan.khan@gmx.com; Tel.: +47-4656-5139
† Authors contributed equally.



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Abstract: A convincing case has been made that the scale of human activity has reached such pervasiveness that humans are akin to a force of nature. How environmental science responds to the many new challenges of the Anthropocene is at the forefront of the field. The aim of this perspective is to describe Anthropocene as a concept and a time period and discuss its relevance to the contemporary study of environmental science. Specifically, we consider areas in environmental science which may need to be revisited to adjust to complexity of the new era: (a) recalibrate the idea of environmental baselines as Anthropogenic baselines; (b) rethink multiple stressor approaches to recognize a system under flux; (c) re-evaluate the relationship of environmental science with other disciplines, particularly Earth Systems Science, but also social sciences and humanities. The all-encompassing nature of the Anthropocene necessitates the need to revise and reorganize to meet the challenge of complexity.

Keywords: environmental science; Earth System Science; multiple stressors; ecosystem health; Anthropocene baselines

1. Introduction

“... as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know.” Donald Rumsfeld, Former US Secretary of Defense, 2002.

It is perhaps an unwritten rule of scientific writing to not start an article with the much-maligned quote of a politician, but these words, whilst confusing when first uttered, may now capture the difficulties of studying environmental science in the Anthropocene. In this new epoch, the key challenge is to understand, assess and mitigate human impacts upon the environment when not all individual stressors can be known. Thus, to paraphrase Mr. Rumsfeld: there are known stressors whose impacts we understand. We also know there are known stressors, but whose impacts are not fully understood (i.e., known unknowns).

However, there are also unknown stressors, either stressors that we are not yet fully aware of or the combined impact of an untold number of stressors within the environment that are difficult to comprehend and disentangle (unknown unknowns). The challenge within the Anthropocene for environmental scientists is to capture and assess all this complexity in which numerous ‘known and unknown’ stressors act simultaneously upon the environment. To do so, it may be necessary to rethink and recalibrate some concepts within the field and re-evaluate the relationship with other areas of research.

Since the turn of the century, a convincing case has been made that the scope of human activity has reached such a pervasive and all-encompassing level that our impacts on the Earth have left an indelible mark on the geological timescale. In their landmark paper “Human Domination of Earth Ecosystems”, Vitousek and colleagues [1] provided an overview of humanity’s effects on the environment at large. To support dramatic population increases, human enterprises such as agriculture, industry, fishing and international commerce, have radically altered the planet by modifying land use, biogeochemical cycles and species composition. Consequently, there are no ecosystems that escape the pervasive human presence [1]. To capture this new reality, the term ‘Anthropocene’ was introduced to refer to the current time-period in which human impacts have become just as important as natural processes [2,3]. This new era is characterized by rapid increase in both the population and consumption of our species to the detriment of the other species that share our planet. However, it is important to note that the relationship between human population increases and environmental degradation is not straightforward, with a multitude of socio-economic and geo-political variables that result in the unequal distribution of impacts [4,5]. Nonetheless, with rates of species loss and decreased biodiversity alarmingly high across both terrestrial and aquatic ecosystems, a sixth great extinction event is being described [1,6].

The primary goal of this short paper is to describe the relevance of the Anthropocene to the contemporary environmental science. In doing so, (1) we provide a brief history of the Anthropocene, as a concept and period, and (2) we examine those areas in environmental science which may need to be revisited in order to adjust to complexity. Specifically, (a) given the pervasiveness of the human footprint there may be a need to recalibrate the concept of environmental baselines; (b) whether (known and unknown) human impacts are so complex and inter-linked that it is time to rethink multiple stressor approaches to recognize a ‘system under flux’; and (c) whether we should re-evaluate the relationship of environmental science with other disciplines and, in particular, Earth Systems Science which views the Earth as a total system of which the environment makes up a portion. This paper does not profess to offer any grand solutions to the topics described herein, but as we progress into the Anthropocene, there is a need to revise and reorganize to meet the challenge of complexity.

2. A Brief Guide to the Anthropocene

The term ‘Anthropocene’ (from the Greek word *Anthropos* ‘human being’ and *-cene* from *-kainos* ‘new’) was introduced during a meeting of the Scientific Committee of the IGBP (International Geosphere Biosphere Programme) in 2000 and immediately gained popularity in referring to the current time-period in which humankind has established itself as the driving force for planetary change [2,3]. However, similar concepts and expressions predate the establishment of the ‘Anthropocene’ term, with Antonio Stoppani (in 1873) referring to an “anthropozoic era” to describe humans as a rival to the greatest forces on earth, and Teilhard de Chardin and Vernadsky (in the 1920s) using the term ‘noosphere’ as a new state of the biosphere in which the role of human thought shapes both its’ own future and the environment [2,3].

Whilst the exact start date of this epoch remains open to debate regarding what stratigraphic layer denotes the transition from the Holocene to the Anthropocene [7], the beginning of industrialization is regarded as an important milestone in the human footprint on this planet [3,7]. James Watt’s invention of the steam engine in 1784 marks the expanded

use of fossil fuels, and consequently increasing atmospheric CO₂ emissions, which has been often used to track the progression of the Anthropocene [3,7]. Steffen et al. (2007) [7] argues that the Anthropocene proceeded in three stages (Figure 1) with Pre- Anthropocene events, including the aforementioned use of fossil fuels, leading into the first stage of the Anthropocene, namely, 'The Industrial Era'. 'The Industrial Era' stage started around 1800 and ended at the end of the Second World War in 1945. During this first stage, energy sources were massively altered by the expansive use of oil, gas and coal in industry. In the second stage, termed 'The Great Acceleration' (starting in 1945), the global human population grew to over 6 billion with a corresponding increase in global economies, and accompanied by changes in land use, deforestation and fossil fuel burning. This stage has been characterized by expansion, discovery, technological advancement, and innovation, but also widespread habitat loss and deterioration of Earth Systems [7,8]. Atmospheric CO₂ levels, an overarching marker of the Anthropocene that reflects the stages of the Anthropocene, rose from <300 ppm at the start of the industrial area to >400 ppm by the end of The Great Acceleration [9]. Further increases are expected as we pass into the Anthropocene's third stage.

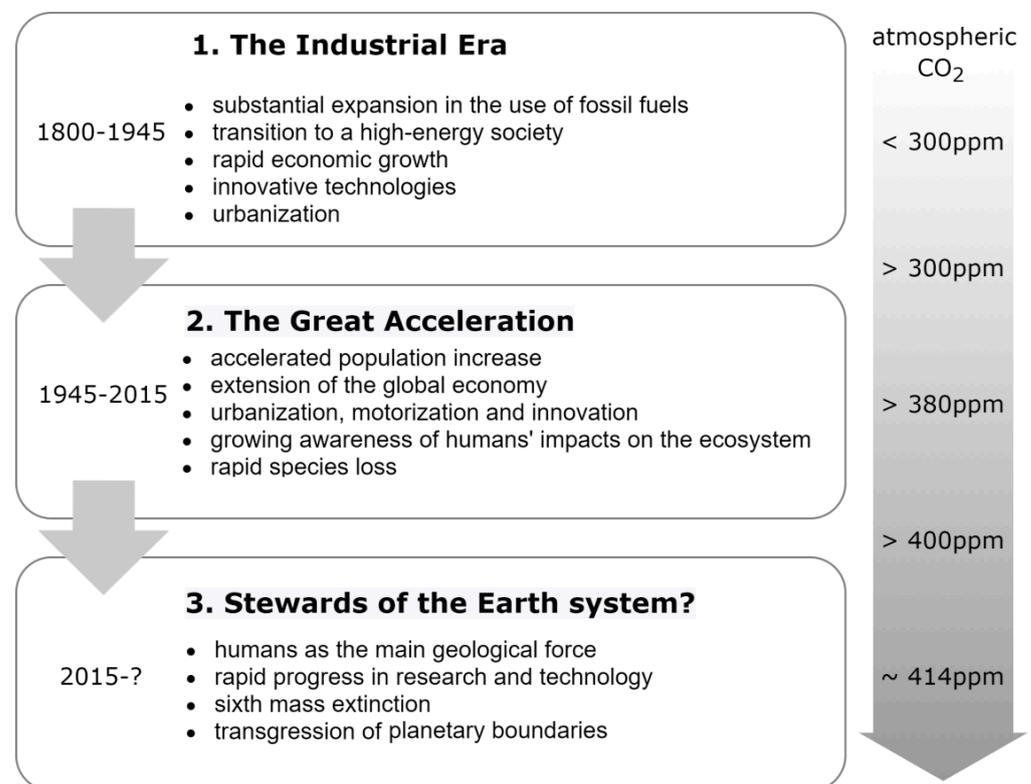


Figure 1. The stages of the Anthropocene [7]. The trajectory of stage 3 where humankind become aware and mitigates anthropogenic impacts upon Earth systems (termed as the 'Stewards of the Earth System' stage) is presently unclear [10]. Atmospheric CO₂ levels that have increased through the stages are presented (values cited from National Oceanic and Atmospheric Administration (NOAA) [9]).

In describing the stages of the Anthropocene, Steffen et al. (2007) [7] suggested that by 2015, we as a species would become aware of our impacts and take decisive action to reverse the trajectory of the Anthropocene. Stage 3 was thus termed 'Stewards of the Earth System' and would be characterized by growing awareness, global information-flow, and more stable and democratic governments placing environmental welfare, and social and cultural concerns at the forefront of their policies. With both the Paris Climate Agreement and United Nations Sustainable Development Goals agreed in 2015, the predicted onset on the third Anthropocene stage appeared on course. However, these agreements have

not yet resulted in the expected ‘tipping point’ towards stewardship and thus it is over the next decade that will either see this vision carried through or missed [10]. In 1948, Fairfield Osborn authored ‘Our Plundered Planet’ and wrote “It is man’s earth now. One wonders what obligations may accompany the infinite possession” [11]. These words encapsulate the notion of stewardship that is required in the coming period.

3. Conceptual Recalibrations for the Anthropocene

With widespread acceptance within the scientific community that we have entered the Anthropocene [12], the question for many areas of science will be how to incorporate the complexities of the new epoch within their research field. This is especially important for environmental science, a subject born from human-driven impacts. In this section, we focus on some of the most prescient challenges that the Anthropocene presents. Firstly, with regard to environmental assessment as a key step in recognizing and mitigating impact, what is the nature of baselines in a system under change? Secondly, is a multiple stressor framework based on the selection of known stressors a realistic model for the Anthropocene? Additionally, thirdly, what relationship should environmental science have with other disciplines and, more controversially, has the multitude and interconnect-edness of stressors, environments and systems on a global scale changed the field from environmental science to one that is part of Earth System Science?

3.1. Recalibrating Environmental Baselines

Assessing the impacts and effects of numerous stressors is one of the biggest challenges facing contemporary environmental science since the proportional risk associated with individual stressors versus their cumulative impacts and their interactions is largely unknown, which limits the applicability and robustness of multiple-stressor ecological risk assessments (ERA) [13–15]. Several authors have highlighted the issues related to incorporating multiple stressors and their interactions into ERA [16–19] and the aim here is not to provide a comprehensive treatise of this topic. For our purposes, it is sufficient to highlight that the task is complicated by data and knowledge gaps regarding the interactions between stressors. A less-considered concern and perhaps where a recalibration needs to occur within the sphere of environmental assessment relates to the reference points that an ERA aims for. More specifically, when protection goals for an ERA are formulated for a given ecosystem, what is the baseline for that assessment? However, to assess a declining state requires an understanding of the concept of ecosystem health. The notion that ecosystems have an optimal healthy, natural state which is important to protect and retain, underlies the concept of ecosystem health.

A healthy ecosystem is characterized as one that is capable of maintaining its vigor (overall metabolism and energy flow) and organization (diversity of interactions between ecosystem components) over time, in the presence of stress (i.e., ecosystem resistance) [20]. Conversely, ecosystem resilience, the ability to recover from disturbance, has two main components: the length of time (RT) that a system needs to recover from stress, and the magnitude of stress (Ms) from which the system can return to its former state [20]. These factors are important because ecosystems can show little change under stress until they reach a critical threshold, related to RT and Ms. After this point, they react in highly unpredictable (i.e., non-linear) ways and this may lead to their collapse [21]. Thus, degradative symptoms characterize many ecosystems that are experiencing the impacts of multiple stressors (both known and unknown). For instance, aquatic ecosystem distress syndrome can include some or most of the following symptoms: alteration in biotic community structure, reduced species diversity, increased dominance by another species, increased dominance by exotic species, shortened food-chain length, increased disease prevalence, and reduced population stability [22].

With the idea of what constitutes a healthy ecosystem in mind, the idealized scenario for an ERA is to return the ecosystem to an optimal state and, therefore, historical baselines are often promoted for multiple stressor assessments. However, there is an argument to be

made that historical baselines are increasingly irrelevant and inappropriate for conserving and managing human-dominated ecosystems, since these systems have been impacted to such a degree that they now constitute a novel ecosystem that has no natural analogue [23]. Furthermore, since the onset of the Industrial Era (Stage 1 of the Anthropocene) and then the dramatic rise of human impacts ('The Great Acceleration' Stage 2 of the Anthropocene) there are virtually no examples left of ecosystems that can be assumed to be in a state representative of conditions in absence of human disturbance [23]. This suggests a lack of suitable contemporary least-disturbed reference points that are representative of ecosystem functioning without human interference. Nonetheless, contemporary baselines are still conducive to 'shifting baseline syndrome' and may lead to unambitious and misguided restoration goals [24], while increasing the risk of the unexpected collapse of ecosystems [25].

Thus, a new pragmatic type of baseline termed 'Anthropocene baselines' may be considered in human-dominated ecosystems [23]. This approach acknowledges that returning to historical states may be impossibly unrealistic since recovery cannot match the trajectory of decline, for two reasons in particular: (1) socioeconomic limitations on reducing anthropogenic pressure and (2) limitations by ecological constraints. In the former case, human habitation may be dependent on the modified ecosystem state so as to make restoration practically but not principally impossible, whilst in the latter case, the modifications may be so extreme that reversal is impossible, either because critical abiotic or biotic remnants of the former state are gone (e.g., keystone species extinction), or because catastrophic non-linear thresholds have otherwise caused a state shift [23]. Since setting the historical baselines as a restoration goal is not feasible, there is a shift from restoring the pre-disturbance ecosystem state to restoring the overall function which may be recoverable by the novel state based on the anthropogenic baseline [23].

3.2. Rethinking Multiple Stressors as a System in Flux

Individual stressors vary in time and space, and in intensity and frequency. Similarly, the responses that these stressors induce at organismal levels and at ecosystem levels depend on the characteristics of the receptors and their environments. The responses are not static, but vary temporally as a function of environmental change, natural variability, life history and community composition [26,27]. In addition, the environmental conditions under which these impacts and interactions occur are undergoing long-term systemic changes, which are themselves stressors. In other words, there are a large number of moving parts. Thus, the following considerations should be contemplated: (1) stressor impacts are not intrinsic stressor characteristics, but arise from complex interactivity between stressors, receptors and their environment; (2) responses to different stressors are highly variable, especially with categorically different stressors; (3) stressors are not universal, they are not necessarily stressors for all species; they may have different effects on different species; (4) stressor impacts can reverberate throughout ecological networks to produce cascading dynamic effects [17].

Thus, it has become increasingly evident that the cumulative impact of several stressors differ from the impact of any single stressor owing to the complexity of environmental systems [13]. This is the basis of the focus on multiple stressors and the frameworks that are used to assess multiple stressor impacts [18,28,29]. The marine environment, as a familiar case study, is arguably amongst the most impacted of ecosystems. This may not be surprising since 60% of human populations reside within 100 km of coastlines [1]. However, for centuries, the marine system had been regarded as an inexhaustible source of food and a convenient dumping ground too vast to be affected by human activity. Yet, it has become increasingly clear that the ocean has limits and that sustainability thresholds have been breached in numerous locales [30,31]. Marine environments have undergone large physical and biogeochemical modifications in response to human induced stressors. These stressors include, but are not limited to, climactic perturbations (i.e., ocean surface warming, changes in ocean salinity, modifications of density structure and stratification, an

increase in dissolved inorganic carbon concentrations, as well as decreasing seawater pH in response to ocean uptake of carbon [30–32], pollution (including both chemical pollutants [33] and plastic debris [34,35]) as well as other stressors such as habitat destruction, decrease in marine primary producers, nutrient input and overfishing that reduce species richness and biodiversity. Figure 2 provides a non-exhaustive overview of the distinct but interconnected stressors that are present in the marine environment. The key point is that no single stressor occurs in isolation, but rather within a highly changeable environmental system [36].

Importantly, there is a divergence between global or systemic stressors (e.g., biogeochemical changes) and local stressors (e.g., pollution) in terms of duration and intensity. Staying with the marine environment (Figure 2), stressors can be grouped in two main categories: (1) a group that acts globally such as increased temperature, ocean deoxygenation (the global trend of decreasing oxygen as a result of ocean warming and increasing stratification) and ocean acidification; (2) a group that acts at a local to regional level but occurs globally, such as overfishing, pollution (chemical and plastic debris) and hypoxia. According to Hamilton (2015) [37], the aggregation of local environments to make up the ‘global environment’ is still insufficient in the face of the Anthropocene, because it pertains to shifts in the functioning of the Earth System. However, given complexity within just a single, albeit vast, environmental compartment, it may become increasingly necessary to rethink the multiple stressor approach and pivot towards considering the environment as a system in a perpetual state of flux [38].

In this constantly changing system, it is the impacts and effects of a combined stressor load that need to be understood, but importantly it is the combination of known and unknown stressors in which complexity lies. The challenge in this epoch (perhaps as it has always been) is to find a way to assess the culmination and complexities of all human-driven impacts on the environment and biota. Kramm et al. [39] recently suggested “complexity is the new normal”, but, perhaps more accurately, complexity needs to be recognized as normal [38]. This realization may suggest a rethinking from multiple stressors to a more holistic all-encompassing approach capable of incorporating unknown factors is now needed.

3.3. Re-Evaluating the Inter- and Intra-Disciplinarity of Environmental Science

A common misconception, according to Hamilton (2015) [37] is to conflate the changes in the environment, however complex, to the Anthropocene. Similarly, it belies the reality of the subject to label any single stressor as indicative of the Anthropocene. The fundamental point concerning the Anthropocene is it encompasses all human impacts upon the totality of Earth Systems rather than simply ‘the environment’ [37]. The distinction is not obviously apparent, but the Earth is a total system of which the environment makes up a portion. It is upon the Earth System, and not its divisions, that humans act upon as a global force [37]. The concept of planetary boundaries illustrates the grand scale upon which Anthropocene-level considerations must be made. In total, nine planetary boundaries have been identified that have the capability to drive the Earth System into a new state: (1) Stratospheric ozone depletion; (2) Loss of biosphere integrity (biodiversity loss and extinctions); (3) Chemical pollution and the release of novel entities; (4) Climate Change; (5) Ocean acidification; (6) Freshwater consumption and the global hydrological cycle; (7) Land system change; (8) Atmospheric aerosol loading; (9) Nitrogen and phosphorus flows to the biosphere and oceans [7,40]. The threshold levels for some of these boundaries have been surpassed, suggesting that the planet is now outside of the safe operating space [40].

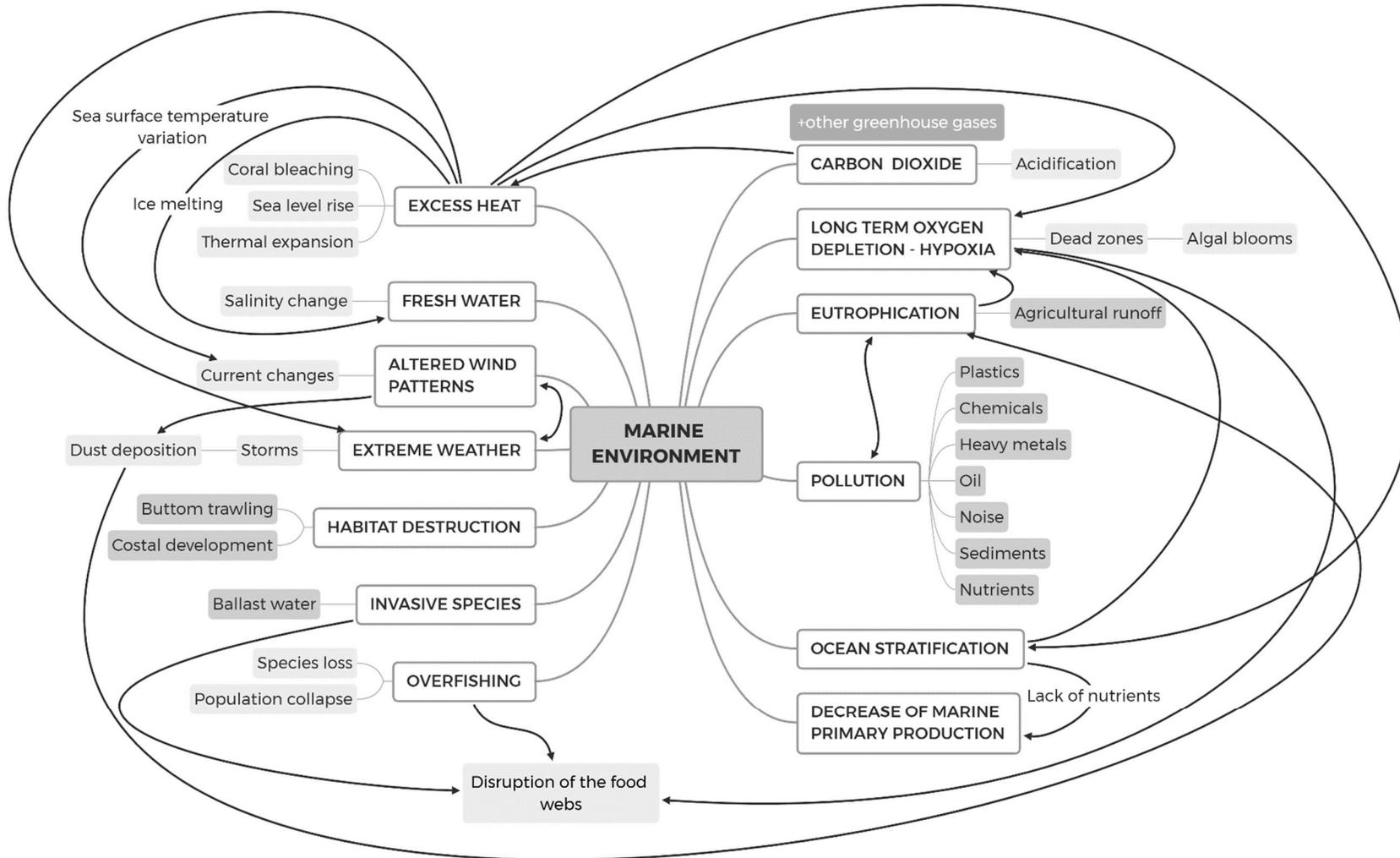


Figure 2. Mind maps of known stressors in the marine environment and their possible interactions.

Each of these boundaries relates to an area of environmental science, i.e., chemical pollution relates to ecotoxicology and freshwater consumption relates to hydrology. Thus, it is obvious to emphasize and embrace the need for inter-disciplinary collaborations. The emergence of Earth System Science as an overarching transdisciplinary subject area consolidates the holistic view that the Earth is a complex adaptive system [41]. Although Earth System Science has its origins in the writings of Stoppani's "Anthropozoic era", and Teilhard de Chardin and Vernadsky's "noosphere", its contemporary challenge now is to provide a unifying space for all disciplines related to biophysical processes and human dynamics to converge to improve the understanding of the Earth System [41].

The 'umbrella' of Earth System Science should include social sciences and humanities disciplines, which have taken an interest in human–environment interactions [42]. Additionally, if the Anthropocene is truly a human-made phenomenon, then studying the trajectory of humanity should go together with studying the impacts of humankind. The broad studies of anthropology, culture, linguistics, and economics describe how our species claimed its place as a dominant force on the planet. Specifically cultural ecology, ecological anthropology and historical ecology tell us from where we emerged and ecological economics, environmental sociology, ecolinguistics may suggest where our species intends to go next. Furthermore, the emergent disciplines of environmental philosophy and ethics, and ecocriticism correspond to the third stage of the Anthropocene and the newfound awareness that will potentially lead to stewardship. The packaging of these subject areas into the more inclusive subject of 'environmental humanities' is underway and from here a plausible step to 'planetary humanities' [42] may mirror the trajectory of environmental sciences into Earth System Science. A re-evaluation of how these overarching fields rely upon each other to respond to the challenges of the Anthropocene is timely.

4. Conclusions

The common thread amongst the considerations made in this paper is the need to further recognize complexity as a necessary factor within the research field. Complexity theory suggests that the greater interconnectedness within a system the more that system is prone to chaotic dynamics and surprising outcomes [43,44]. As illustrated in this paper (and many others), the Anthropocene presents the Earth System as an extraordinarily complex changeable system and, thus, traditionally held ideas of multiple stressors interacting upon the environment and of historical baselines as ideal reference points of ecosystem health need to be revised. The complexity of the Earth as an adaptive system made up of numerous inter-connected components means that all ecosystems exist within a perturbed state. The analysis of complexity also needs to extend to the complexity of human behavior from which a profound awareness of anthropogenic damage may lead us to become 'Stewards of the Earth System'.

This perspective has started from the rather uncritical vantage point that the Anthropocene has dawned and with it a new level of complexity needs to be incorporated into our discipline. However, there is a contrarian argument to be made, that even if the Anthropocene has stared—so what? Environmental science, science in general since the time of Aristotle, has always been burdened with the knowledge that the natural world contains variables that are known to us and variables that are not. Is this not the natural limitation of scientific knowledge? Does the Anthropocene really bring something new or require special consideration in terms of understanding complexity? Moreover, is it presumptuous of us to think that we can understand complexity, if no reasonable methods exist to capture it? Regarding the specific cases described in this paper, it could be argued that all baselines are, to some degree, arbitrary and furthermore it is not possible to study the impact of multiple stressors or a truly fluctuating system without an agreed upon baseline—how else would change be recognized? Thus, there is a danger that the Anthropocene provides the opportunity to reinvent concepts and terms without changing practices—a semantic change, but not a real one.

The aim of this perspective is to start a discussion on whether and how the Anthropocene now pervades our thinking. It is possible that at end of this discussion the ‘so what?’ arguments prevail, but inter- and intra-disciplinary conversations need to be held. At the very least, the interdependence between subject areas, such as global change, environmental science, human health, and the broad humanities, need recognition and discussion [45]. The idea that environmental science sits within the broader scope of Earth System Science is intriguing and certainly requires greater debate within the field. However, a positive outcome of accepting such a notion would be to facilitate the inter- and intra-disciplinary collaborations that are required to study the Anthropocene in its fullest sense. The paring of Earth System Science with a corresponding humanities field such as ‘Planetary Humanities’ [42] may well reconcile the study of human civilization with the impact of human civilization. The greatest challenge, arguably that our species has ever faced, is of our own making. By seeing our field as part of a broader research scheme and rethinking, recalibrating and re-evaluating viewpoints that define the meaning and scope of the environment (Earth System), the capacity to respond to the challenges of the Anthropocene may well be enhanced.

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