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GUEST EDITORIAL

Earth steward: Will Steffen's contributions to Earth System Science, governance and law

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INTRODUCTION

In January 2023, the world lost one of its most influential environmental scientists, Will Steffen. Recognised by his peers as the 'Father of Earth System Science', Steffen exemplified the ethic of planetary stewardship (Stockholm Resilience Centre 2023; Fig. 1). This ethic was especially evident, not only in Steffen's scholarship, but also in his contributions to creating institutions that respect the reality of a single integrated Earth System and aim to govern human behaviour accordingly (Steffen 2016). This article commemorates Will Steffen's scientific work in Earth System Science, and places it in the larger context of his contributions to governance and law.

Fig. 1 Will Steffen (1948–2023) was the Inaugural Director of the Australian National University Climate Change Institute (Copyright Will Steffen)

THE ANTHROPOCENE AND THE GREAT ACCELERATION

Until the 2010s, the concept of the Anthropocene was little known beyond a small community of Earth scientists (Steffen et al. 2011a; Steffen 2021). The term would probably have remained obscure if not for Steffen. Through a series of highly-cited publications, Steffen and his colleagues convinced audiences, both inside and outside of academia, that the ongoing expansion of human societies is putting the stability and integrity of Earth Systems at risk. Steffen's message was built on the theorization, empirical foundation, and implication of what he called "the great acceleration" (Steffen et al. 2007, 2015b) (Fig. 2).

The empirical foundation came first. More than two decades ago, Steffen and his colleagues made a striking observation that around the year 1950, the expansion of human activity across global socio-economic indicators (e.g. energy use, population growth and gross domestic product) coincided with an increase in degradation across biophysical (i.e. environmental, and climatic) indicators. This phenomenon was characterized by exponential growth curves, across all "human" activities, from paper production to fertilizer use, and corresponding increases across Earth system trends, ranging from atmospheric carbon dioxide, marine fish capture, nitrogen use and terrestrial biodiversity loss. The curves manifested as mirror images in social and biophysical trends, and they all began around the same time—the 1950s. The dataset, particularly the graphs depicting the acceleration (Fig. 2), now hold canonical status because they helped establish the

foundation for the burgeoning scientific disciplines of Earth System Science and Sustainability Science.

Steffen and his colleagues first published their data and findings in the book *Global Change and the Earth System: A Planet Under Pressure* (Steffen et al. 2004). This book synthesized a decade of research performed within the International Geosphere-Biosphere Programme. However, it was only a year later, during a meeting chaired by Steffen ('the Dahlem workshop'), that the concept of "the great acceleration" was coined (Head et al. 2022, p. 360) and discussed in relation to the Anthropocene (Hibbard et al. 2007). In 2007, the concept was finally introduced to the academic community, when Steffen, together with Paul Crutzen and John McNeill, published *The Anthropocene: Are humans now overwhelming the great forces of Nature?* (Steffen et al. 2007) in *Ambio*. This article became one of Steffen's most widely read and cited works, and is currently the most cited paper in *Ambio*'s 50-year history, with 4374 citations according to Google Scholar at the time of writing.

Although the idea of the Anthropocene had been established in the Earth System Science community for over a decade, it was only in May 2019 that a vote was carried out under the auspices of the Sub-commission on Quaternary Stratigraphy of the International Union of Geological Sciences and International Commission on Stratigraphy to formalize the Anthropocene as a new geological epoch. The vote resulted in a strong majority in support of its formalization as the current geological epoch, although that process has not yet been finalized. Support for the characterisation of the new epoch was based on several years of scientific synthesis and assessment by the Anthropocene Working Group.[1] The group received significant scientific inputs and active engagement from Steffen, and is now focusing on the Great Acceleration as the exit point from the Holocene (Waters and Turner 2022; Head et al. 2022).

PLANETARY BOUNDARIES

Will Steffen has also played a central role in the advancement of another notion that came to occupy a central place within Earth System Science: planetary boundaries (Rockström and Steffen et al. 2009; Steffen et al. 2015a).[2] Here Steffen was a strong advocate for taking the Holocene as the benchmark for a desired state of the planet that can support human development. His argument—as straightforward as it is unnerving—was that the Holocene is the only state of the planet that can support life as we know it. From this it follows that humanity's challenge (and the objective of the planetary boundaries framework) is to scientifically define a safe operating space for human development that would keep the planet in a "Holocene-like" state (Steffen et al. 2015a). This wording might appear as linguistic fine-toothing, but is, in fact, profoundly important. By using the word "Holocene-like" Steffen acknowledged that in the Anthropocene, humanity has irreversibly transformed the Earth System, making a return to a "pristine" Holocene state impossible. Therefore, he pioneered efforts to ensure the planet remained within an inter-glacial regime where the ecological and physical functions of the Earth System are stable and resilient.

With this conviction, Steffen was, until the very end, actively involved in the ongoing, first scientific assessment of the variability range for planetary boundaries during the Holocene. He advanced understanding of the risks associated with pushing the Earth System into an irreversible drift away from a Holocene-like inter-glacial state, due to positive feedbacks gaining dominance over negative feedbacks.

In the "Hothouse Earth" hypothesis (Steffen et al. 2018), Steffen and colleagues posed the question: if anthropogenic climate forcing (through fossil-fuel burning and land use change) reached an equivalent to 2 °C, how would the Earth System respond? The answer was that it is possible that breaching a planetary threshold could trigger Earth System tipping points such as large forest biomes and boreal permafrost, to reverse feedbacks and reinforce global warming. Such an event could initiate a cascade of multiple tipping points, resulting in the crossing of other planetary thresholds and an irreversible shift towards a "Hothouse" Earth state that would be hostile to humanity and life in general. This is not suggesting a "runaway" Earth, but rather a shift in Earth resilience from dampening to self-reinforcing warming.

As of March 2023, Steffen's paper on "Hothouse Earth" (Steffen et al. 2018) has garnered almost one million views, a remarkable feat for a scientific publication. The paper's core message is clear and resounding: concerted human effort is necessary to prevent the Earth System from crossing critical thresholds and maintain it in a habitable, "Holocene-like" state. To that end, Steffen has long been an advocate for a "new responsibility" that extends to the entire planet, which he captured through the idea of planetary stewardship (Steffen et al. 2011b; Steffen 2021).

Will Steffen did not shy away from voicing his opinion on how this new responsibility should be shared in today's unequal world. In the collaborative work on planetary

[1] http://quaternary.stratigraphy.org/working-groups/anthropocene/

[2] In addition to planetary boundaries, Steffen also connected the idea of the Anthropocene with a number of other iconic sustainability concepts, such as polycentric governance (Ostrom 2010), complex systems thinking, tipping points (Lenton et al. 2008) and critical transitions (Scheffer 2009); and considered the implications of the Anthropocene trajectory for life on Earth (see Steffen et al. 2011b, 2015b; 2018; 2021; Chapin III et al. 2010; Folke et al. 2021).

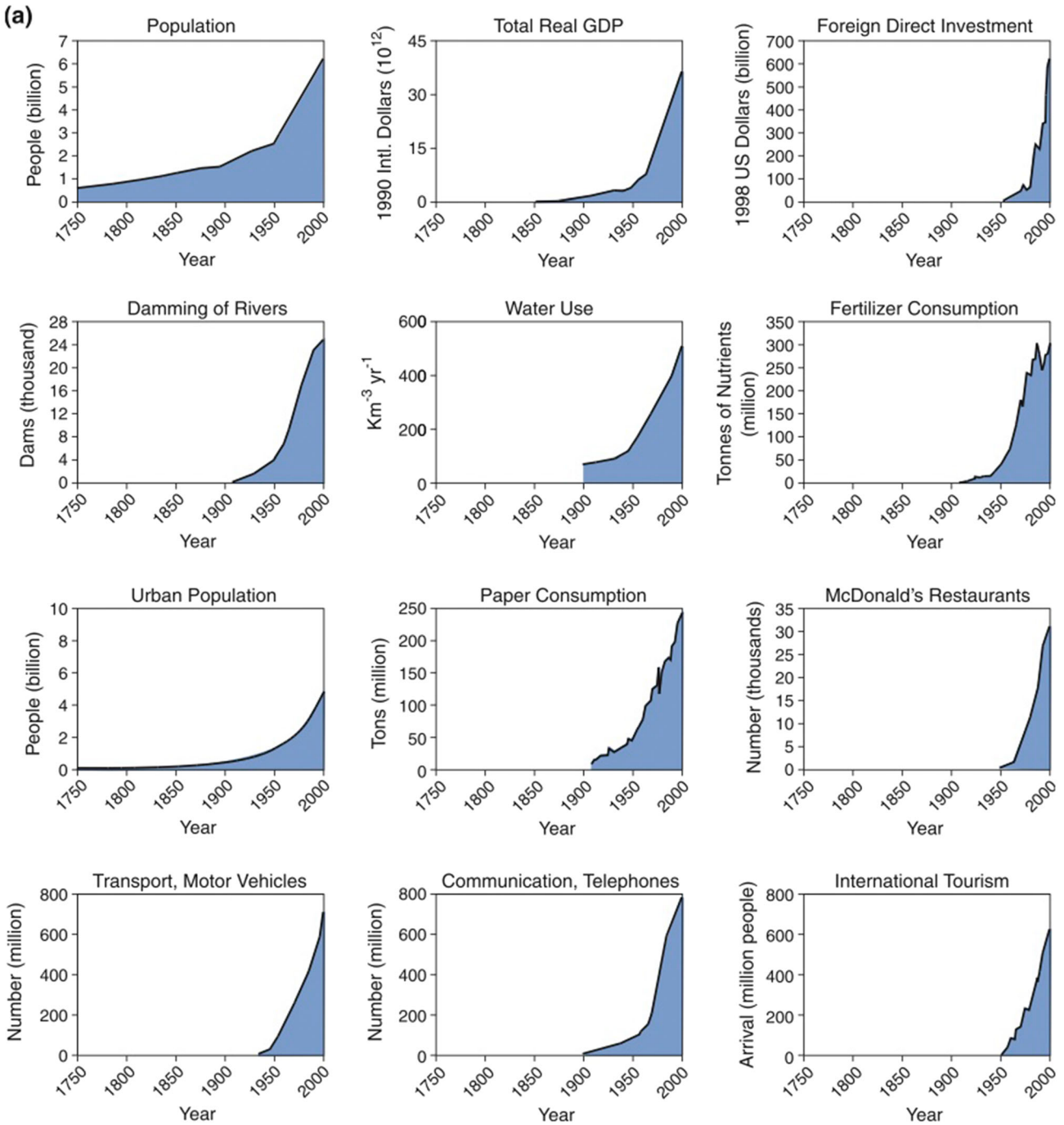


Fig. 1 **a** The increasing rates of change in human activity since the beginning of the Industrial Revolution to 2000. Significant increases in rates of change occur around the 1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history (Steffen et al. 2004, and references therein). In the following part figures, the parameters are disaggregated into OECD (wealthy) countries (*blue*) and non-OECD (developing) countries (*red*); **b** Population change from 1960 through 2009, in 1000 millions of people (World Bank 2010); **c** Increase in real GDP from 1969 through 2010, in trillions 2005 USD (USDA 2010); **d** Communication: increase in telephones (millions), both land-lines and mobile phones, from 1950 through 2009 (Canning 1998; Canning and Farahani 2007; ITU 2010)

Fig. 2 The Great Acceleration (retrieved from Steffen et al. 2011b, pp. 742–745)

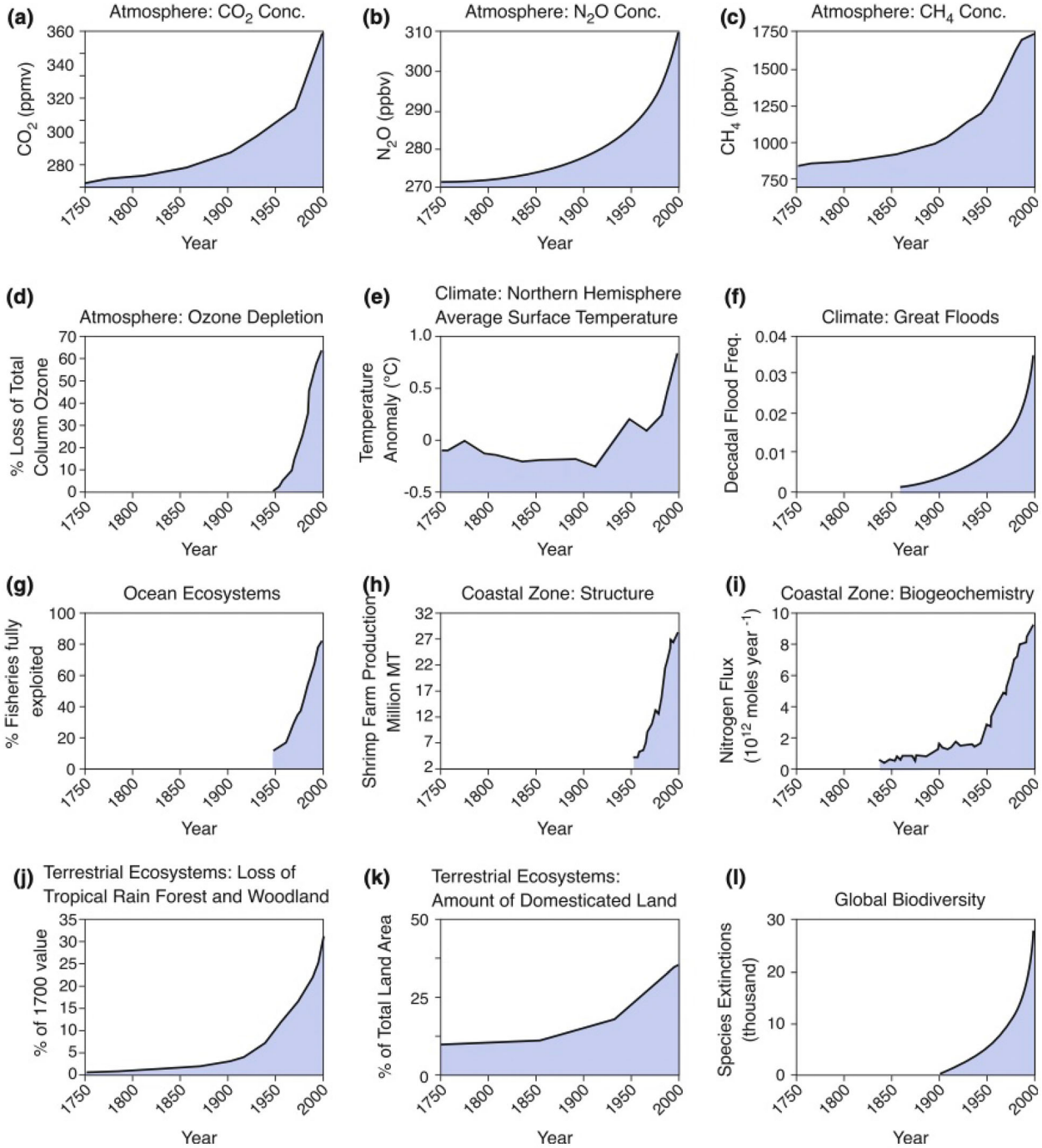
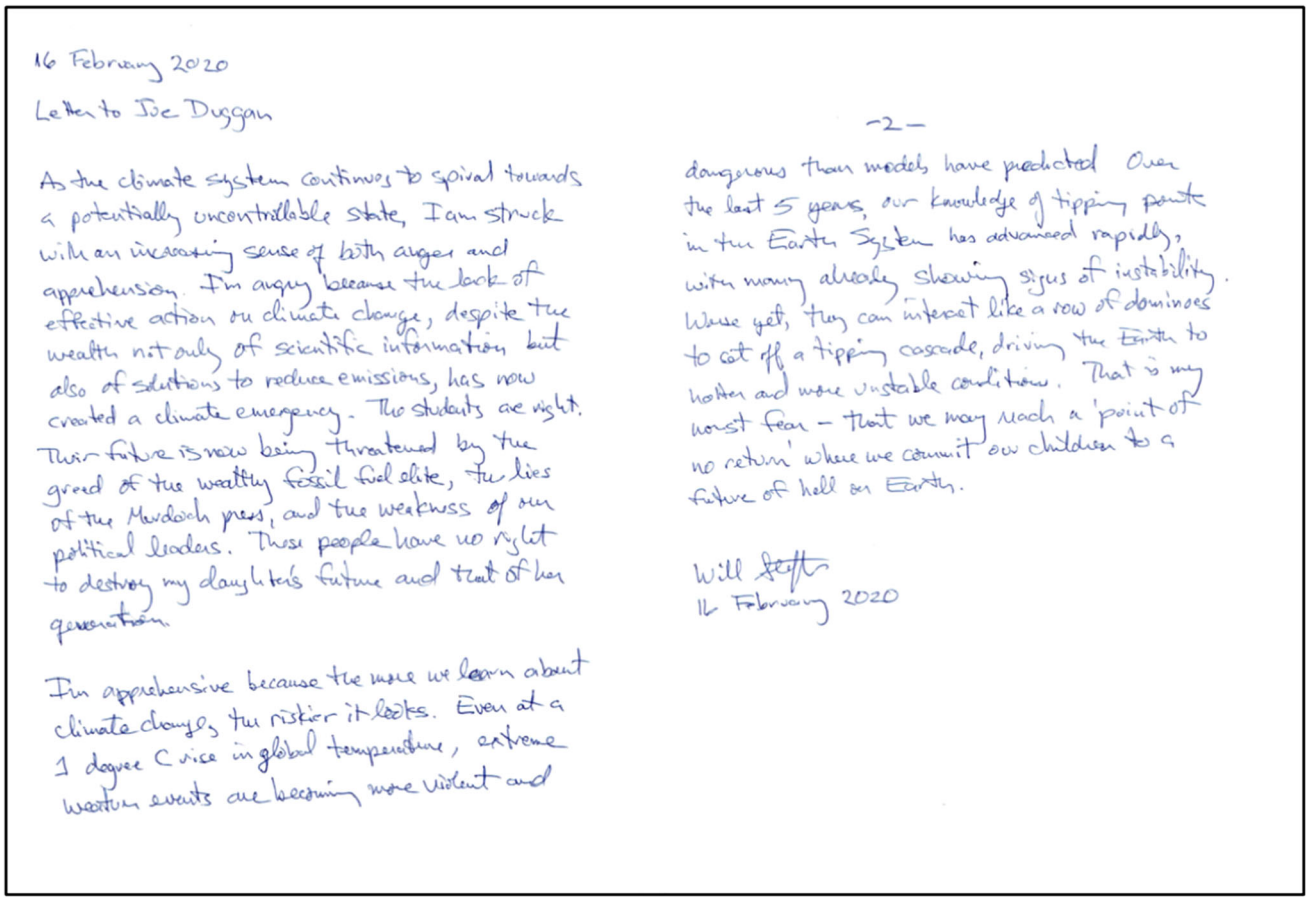


Fig. 3 Global-scale changes in the Earth System as a result of the dramatic increase in human activity: **a** atmospheric CO_2 concentration, **b** atmospheric N_2O concentration, **c** atmospheric CH_4 concentration, **d** percentage total column ozone loss over Antarctica, using the average annual total column ozone, 330, as a base, **e** northern hemisphere average surface temperature anomalies, **f** natural disasters after 1900 resulting in more than 10 people killed or more than 100 people affected, **g** percentage of global fisheries either fully exploited, overfished or collapsed, **h** annual shrimp production as a proxy for coastal zone alteration, **i** model-calculated partitioning of the human-induced nitrogen perturbation fluxes in the global coastal margin for the period since 1850, **j** loss of tropical rainforest and woodland, as estimated for tropical Africa, Latin America and South and Southeast Asia, **k** amount of land converted to pasture and cropland, and **l** mathematically calculated rate of extinction (Steffen et al. 2004, and references therein)

Fig. 2 continued


16 February 2020

Letter to Joe Duggan

As the climate system continues to spiral towards a potentially uncontrollable state, I am struck with an increasing sense of both anger and apprehension. I'm angry because the lack of effective action on climate change, despite the wealth not only of scientific information but also of solutions to reduce emissions, has now created a climate emergency. The students are right. Their future is now being threatened by the greed of the wealthy fossil fuel elite, the lies of the Murdoch press, and the weakness of our political leaders. These people have no right to destroy my daughter's future and that of her generation.

I'm apprehensive because the more we learn about climate change, the riskier it looks. Even at a 1 degree C rise in global temperature, extreme weather events are becoming more violent and

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dangerous than models have predicted. Over the last 5 years, our knowledge of tipping points in the Earth System has advanced rapidly, with many already showing signs of instability. Worse yet, they can interact like a row of dominoes to set off a tipping cascade, driving the Earth to hotter and more unstable conditions. That is my worst fear – that we may reach a 'point of no return' where we commit our children to a future of hell on Earth.

Will Steffen

16 February 2020

Fig. 3 Steffen's letter to the project "Is This How You Feel?" (courtesy of Joe Duggan, retrieved from https://www.isthishowyoufeel.com/ITHYF5.html#Will)

boundaries, Steffen and his colleagues deliberately excluded the "deeper issues of equity and causation" from the framework's scope (Steffen et al. 2015a, pp. 1259855–8). They emphasized that the framework "does not dictate how societies should develop", which they acknowledged as being "political decisions that must include consideration of the human dimensions, including equity" (Steffen et al. 2015a, p. 736). However, in the paper co-authored with Mark Stafford-Smith, we get a glimpse of what Steffen perceives as just and effective when they argue that it is "in the self-interest of wealthy nations to achieve a more spatially equitable world in terms of access to resources and ecosystem services" (Steffen and Stafford Smith 2013: 403). He argued that "combining social equity considerations with the biophysical planetary boundaries approach may […] constitute a necessary, and perhaps even sufficient, condition for achieving global sustainability".

Will Steffen's deep concern about the lack of political action also comes through in his reflection written for *Ambio*'s 50th anniversary collection, where he returns to two of his *Ambio* publications on the Anthropocene. He admits to fear that many of the warnings that he and fellow Earth System scientists have sounded since the early 2000s have fallen on deaf ears. He ends the paper by urging scholars and policy makers to focus on "solutions, such as social tipping points and fundamental, rapid transformations, rather than yet another diagnosis of the problem" (Steffen 2021, p. 1787) because time is running out.

The same spirit marks Steffen's emotionally powerful letter to the project "Is This How You Feel?" (Fig. 3). Here, Steffen notes down his anger and apprehension. Anger at the lack of climate action despite overwhelming scientific evidence and solutions. Apprehension at what greater understanding of the Earth System heralds for the closing window of opportunity to sustain a liveable planet.

EARTH SYSTEM LAW AND GOVERNANCE

Will Steffen's work also had a profound influence on disciplines outside Earth System Science. The most notable of these are in law, governance and political science. Steffen

was a member of the Earth System Governance Network's Lead Faculty. Here his research offered natural science-based foundations to interrogate the social and political dimensions of Earth System change.[3] More particularly, Steffen's research helped social scientists to understand the multi-scalar and temporal justice implications of Earth System change for humans and non-humans alike. But perhaps most importantly, Steffen's work reinforced the realisation of continuously deteriorating planetary stability and emphasised the urgent need for humanity to become better and more responsible Earth stewards, through the many social institutions we use to steer human behaviour.

The influence of Steffen's work was particularly evident in the legal domain. The planetary boundaries concept, for example, offers lawyers a useful framework to rethink the limits and potential of law to keep humanity within a "safe operating space" (French and Kotzé 2021) and to uphold legal rights to a clean, sustainable and healthy environment (Preston 2023). New legal imaginaries such as Anthropocene law (Aragão 2016; Vermeylen 2017; Kotzé and French 2018); planetary boundaries law (Chapron et al. 2017; Fernandez and Malwe 2018); and Earth-centered law (Bosselmann 2016) have emerged as new legal paradigms situated within the context of the Anthropocene. More specifically, Steffen's work on a human-dominated Earth System inspired lawyers to explore, within the context of the growing field of Earth System law (Kotzé and Kim 2019), how law could account better for non-humans (Gellers 2021; Petersmann 2021). Earth System law recognises that "environmental law", despite its modest advances, has failed to address the cumulative decline in planetary stability and associated levels of deepening global injustices between species, the Global North and Global South, and present and future generations. To this end, Steffen's work has encouraged an increasingly urgent search for alternative legal modalities that fit with the reality of the Anthropocene (Kim 2021). These alternative modalities are centred on, and oriented by, the reality of an interconnected Earth System and the multiple complex consequences of change that law, as a social institution, must address within the larger context of Earth System governance (Biermann 2021). They offer an important foundation to critique the shortcomings of existing law and governance, and possible means of reform to strengthen humanity's response to the planetary crisis.

Will Steffen lent his direct support for advancing these efforts (Magalhães 2016). One example is his role as the co-chair of the Scientific Committee of the Common Home of Humanity (Magalhães and Steffen 2020). The mission of this initiative is "to achieve the legal definition and recognition of a Stable Climate as a Global Common that spans across borders as the structural basis for building a regenerative economy and a new global governance system for Humanity".[4] His legacy lives on in the ongoing work of those involved in this initiative.

EXPERT WITNESS STATEMENTS

Will Steffen also contributed to the translation of Earth System Science concepts into law through his expert scientific evidence in climate change cases litigated before Australian and New Zealand courts. The best known example is his witness statement in the case of the Rocky Hill Coal Project, Gloucester Resources Limited v Minister for Planning (2019) 234 LGERA 257; [2019] NSWLEC 7, in the Land and Environment Court of New South Wales (the Court).[5]

In this case the Gloucester Resources Limited (GRL) had applied for consent to develop an open cut coal mine in Gloucester, New South Wales (NSW). The NSW Minister for Planning had refused the application. GRL appealed to the Court. A local community group, Groundswell Gloucester Inc, was joined as a party to the appeal. The group submitted that the greenhouse gas (GHG) emissions of the project would adversely impact on measures to limit anthropogenic climate change. The project's cumulative GHG emissions would be inconsistent with achieving the temperature and time targets under the Paris Agreement and NSW government policies that endorsed those targets. The community group argued that to reach the goal of limiting the increase in global average temperature to well below 2 °C above pre-industrial levels (the temperature target in article 2 of the Paris Agreement) by 2050 (the time target in Article 4), no new coal mines, including the Rocky Hill Coal Mine, could be approved.

Steffen's expert evidence was foundational for the success of the group's argument. He was able to translate Earth System Science from the global to the local, from the general to the particular. In his witness statement,[6] Steffen explained the science of climate change, including that the major cause is anthropogenic GHG emissions (summarised in [431]–[434]). He summarised the impacts of climate change, not only globally (at [435]–[436]) but also in Australia and NSW (at [438]).

Steffen addressed the critical decision-making questions the Court needed to answer in determining the likelihood and acceptability of the project's climate change impacts. The first question was to identify the GHG emissions of the project that needed to be considered at law. This was

[3] https://www.earthsystemgovernance.org/

[4] http://commonhomeofhumanity.org/

[5] http://envlaw.com.au/gloucester-resources-case/

[6] Available at: http://envlaw.com.au/wp-content/uploads/gloucester4.pdf

primarily a legal question but there was a factual component that Steffen addressed.

The project's GHG emissions would be both direct and indirect. The direct emissions, referred to as Scope 1 emissions, were from undertaking mining operations. The indirect emissions were upstream emissions, referred to as Scope 2 emissions, from the generation by coal-fired power stations of electricity used in mining operations, and downstream emissions, referred to as Scope 3 emissions, from the combustion of the coal mined. The Court held that both direct and indirect emissions from the project were required by law to be considered (at [486]–[513]). Steffen's evidence as to the homogeneity of all GHG emissions, both direct or indirect emissions, assisted the Court in reaching the conclusion that all emissions needed to be taken into account.

The second question was to quantify the cumulative GHG emissions over the duration of the project. The mine would produce 21 million tonnes over 16 years (at [4]). The estimated cumulative emissions were nearly 38 million CO2 equivalent tonnes (at [429],[515]).

The third question was to evaluate the impact on climate change of these cumulative GHG emissions. This required some yardstick. Steffen provided two. The first was the simple causal link between all GHG emissions and climate change. As Steffen observed, "all emissions are important because cumulatively they constitute the global total of greenhouse gas emissions, which are destabilising the global climate system at a rapid rate" (at [450]). The Court relied on Steffen's evidence in rejecting GRL's "drop in the ocean" argument that the project's GHG emissions would be so insignificant relative to total global GHG emissions as not to contribute meaningfully to climate change (at [515]). The second yardstick Steffen proffered was the global carbon budget approach to estimate the GHG emissions reductions required to meet the 2 °C temperature target in the Paris Agreement. It is based on the well-proven relationship between cumulative GHG emissions and the increase in global average temperature (at [441]). Steffen estimated the remaining budget at 215 Gt C, which at the current rate of GHG emissions of 10 Gt C per year would be consumed in just over two decades (by 2040) (at [443]).

Steffen explained that "the clear message from any carbon budget analysis" is that fossil fuel combustion must be phased out quickly, which in turn necessitates leaving most of the world's remaining fossil fuel reserves in the ground, unburned, if the Paris Agreement temperature target is to be met" (at [445]–[446]). Hence, no new fossil fuel developments should be allowed, including the Rocky Hill Coal Mine (at [447]–[450]). The Court accepted Steffen's evidence (at [526]–[527]), although it refined his analysis in refusing consent to the mine (at [552]–[556]).

The Court's reasoning and decision, based on Steffen's evidence, has since then been applied by other courts, including by the Land Court of Queensland in Waratah Coal Pty Ltd v Youth Verdict & Ors (No 6) [2022] QLC 21. Steffen's witness statement goes beyond determining what the facts are by communicating both the magnitude and urgency of climate change. His transparent, independent and evidence-based reasoning will live on to help courts now and in the future reach decisions that are just from an Earth System perspective.

CONCLUSION

Will Steffen's capacity to discover, explain, and communicate complex social-ecological issues at the planetary scale was profound and ground-breaking. His scholarship has not only changed the way we conceptualise our rapidly changing Earth but also the responsibility of humanity in this context. His legacy is in his scientific contributions and his unique capacity to communicate complex science to broader publics. Steffen will also be remembered for his inspiration across disciplines. And, in combination with his contributions to legal and governance processes, to searching pathways towards better futures for environment and society.

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