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The emergence and evolution of Earth System Science

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Abstract

Earth System Science (ESS) is a rapidly emerging transdisciplinary endeavour aimed at understanding the structure and functioning of the Earth as a complex adaptive system. Here we discuss the emergence and evolution of ESS, outlining the importance of these developments in advancing our understanding of global change. Inspired by early work on biosphere-geosphere interactions and by novel perspectives such as the Gaia hypothesis, ESS emerged in the 1980s following demands for a new "science of the Earth". The International Geosphere-Biosphere Programme soon followed, leading to an unprecedented level of international commitment and disciplinary integration. ESS has produced new concepts and frameworks central to the global change discourse, including, the Anthropocene, tipping elements and planetary boundaries. The grand challenge for ESS is to achieve a deep integration of biophysical processes and human dynamics to build a truly unified understanding of the Earth System.

[H1] Introduction

For tens of thousands of years, indigenous cultures around the world have recognised cycles and systems in the environment, and that humans are an integral part of these. However, it was only in the early 20th century that contemporary systems thinking was applied to the Earth, initiating the emergence of Earth System Science (ESS). Building on the recognition that life exerts a strong influence on the Earth's chemical and physical environment, ESS originated in a Cold War context with the rise of environmental and complex system sciences[1-3].

The ESS framework has since become a powerful tool for understanding how Earth operates as a single, complex adaptive system, driven by the diverse interactions among energy, matter and organisms. In particular, it connects traditional disciplines — which typically examine components in isolation — to build a unified understanding of the Earth. With human activities increasingly destabilising the system over the last two centuries, this perspective is necessary for studying global changes and their planetary-level impacts and risks, including phenomena such as climate change, biodiversity loss, and nutrient loading. Indeed, one of the most pressing challenges of ESS is to determine whether past warm periods in Earth history are a possible outcome of current human pressures and, if so, how they best can be avoided.

In this Perspective, we explore the emergence and evolution of ESS, outlining its history, tools and approaches, new concepts, and future directions. We focus largely on the surface Earth System, that is, the interacting physical, chemical and biological processes among the atmosphere, cryosphere, land, ocean and lithosphere. Although other definitions of ESS include the whole planetary interior[4-5], the processes of which become increasingly important as the timescale of consideration increases[6], we focus on the surface where the majority of materials are cycled within the Earth System.

[H1] The emergence of ESS

We begin with a brief history of ESS, outlining important historical phases, including: precursors and beginnings up through the 1970s; the founding of a new science in the 1980s; global expansion in the 1990s; and present day ESS. A timeline of key events, publications and organisations that characterise the evolution of ESS is shown in Figure 1.

[H2] Beginnings (up through the 1970s)

Past conceptualisations of the Earth formed important precursors to the contemporary understanding of the Earth System. Examples include J. Hutton's 1788 'theory of the Earth', Humboldtian science in the 19th century, and V. Vernadsky's 1926 'The Biosphere'[7]. Understanding the historical roots of ESS, however, requires a focus on the second half of the 20th century when, in a Cold War context, important shifts occurred in the Earth and environmental sciences[8]. Thanks to military patronage taking precedence over traditional sources of funding for Earth sciences, geophysics experienced unprecedented growth[9]. Moreover, surveying and monitoring the global environment became a strategic imperative, providing information that would later be useful for contemporary ESS as it began to emerge[10,11].

In the middle of the 20th century, international science started to develop, epitomised by the International Geophysical Year (IGY) 1957-58[12]. This unprecedented research campaign coordinated the efforts of 67 countries to obtain a more integrated understanding of the geosphere, particularly glaciology, oceanography and meteorology. One of the key impacts of the IGY was a lasting transformation in the practices used to understand how the Earth works. The interpretative and qualitative geological and climatological research based on field observations - as classicly studied by geographers - was replaced by field instrumentation, continuous and quantitative monitoring of multiple variables, and numerical models[13]. This transformation led to the two contemporary paradigms that structure the Earth sciences: modern climatology and plate tectonics[14,15].

Ecology and environmental sciences also developed rapidly[16]. Ecosystem ecology emerged with the work of G. E. Hutchinson and the brothers H. Odum and E. Odum, and was supported by the Scientific Committee on Problems of the Environment (SCOPE). Large projects such as the International Biological Programme (IBP)[17] were major steps towards a global ecological study. These efforts provided the basis for understanding the role of the biosphere in the functioning of the Earth System as a whole[18-22].

The 1960s and 1970s were marked by a broadening cultural awareness of environmental issues in both the scientific community and general public. Driving this increased awareness were the publication of R. Carson's *Silent Spring*[23], the 'Only one earth' discourse at the 1972 United Nations Conference on the Human Environment[24], the first alerts on ozone depletion and climatic change[25,26], and the Club of Rome's publication of the *Limits to Growth* report[27]. The *Limits to Growth* report warned of the finitude of economic growth due to resource depletion and pollution[28]. Visual images of the Earth, in particular the 'Blue Marble' image taken by the crew of the Apollo 17 spacecraft on 7 December 1972, sharpened the research focus on the planet *as a whole* and highlighted its vulnerability to the general public[29-31].

Amidst these developments, in 1972 J. Lovelock introduced the term Gaia as an entity comprised of the total ensemble of living beings and the environment with which they interact, and hypothesised that living beings regulate the global environment by generating homeostatic feedbacks[32]. Although this hypothesis generated scientific debate and criticism[33,34], it also generated a new way of thinking about the Earth that emphasized the major influence of the biota on the global environment and the importance of the interconnectedness and feedbacks that link major components of the Earth System[35-37].

The scientific developments up to 1980 - from Vernadsky's pioneering research, through large-scale field campaigns and the emerging environmental awareness of the 1970s, to Lovelock's Gaia - led to a new understanding of the Earth, challenging a purely geophysical conception of the planet and transforming our view of the environment and nature[16,38]. The stage was now set for the introduction of a new science - a more formal and well organised Earth System science.

[H2] Founding a new science (1980s)

Triggered by the growing recognition of global changes such as human-driven ozone depletion and climatic change, a series of workshop and conference reports in the 1980s called for a new "science of the Earth"[39-40]. The calls were based on the acknowledgement that if a new science was to be founded, it would need to be based on the newly emerging recognition of Earth as an integrated entity: the Earth System.

At NASA, the new scientific endeavor was named "Earth system science". The NASA Earth System Science Committee was established in 1983[41], aimed at supporting the Earth Observing System (EOS) satellites and associated research that helped drive the evolving definition of ESS via linked observations, modelling and process studies. The NASA-led research initiatives also developed new visual representations of the Earth System, most famously the NASA Bretherton Committee diagram[4](Fig, 2). The Bretherton diagram (as it is often referred to) was the first systems-dynamics representation of the Earth System to couple the physical climate system and biogeochemical cycles through a complicated array of forcings and feedbacks. Humans constituted a single box of their own connected to the rest of the Earth System through three forcings (carbon dioxide (CO_2), pollutant emissions, and land-use change) and their corresponding impacts[42]. The Bretherton diagram epitomised the rapidly growing field of ESS through its visualisation of the interacting physical, chemical and biological processes that connect components of the Earth System and through the recognition that human activities were a significant driving force for change in the system.

Reports, workshops and conferences all agreed that ESS, given the very nature of its object, should be interdisciplinary and international: interdisciplinary given that interactions between processes don't respect disciplinary barriers, and international because global phenomena are studied. Whilst interactions *within* individual components of the Earth had already been studied, the emphasis of ESS was in understanding the multi-component interactions *among* physical, chemical and biological processes. This created a significant challenge in bringing different disciplines together to study the Earth System as a whole.

The challenge of international commitment and disciplinary integration was addressed by the International Council for Science (ICSU) in 1986 with the formation of the International Geosphere-Biosphere Programme (IGBP) [5,43-45], which joined the World Climate Research Programme (WCRP), formed in 1980 to study the physical climate component of the Earth System [46]. IGBP was originally structured around a number of core projects on biogeochemical aspects of the Earth System: ocean carbon cycle, terrestrial ecosystems, atmospheric chemistry, the hydrological cycle, and others. Two projects of particular importance were PAGES (past global changes) and GAIM (global analysis, interpretation and modelling) given their locus of strong disciplinary integration. In addition, IGBP developed a dedicated project on data and information systems (DIS), especially remotely sensed data, to support the research.

This convergence of disciplines accelerated the evolution of ESS, evident as a transition from isolated process studies to interactions between these processes and increasingly global-level observations, analyses and modelling[47]. ESS thus facilitated the transformation from interdisciplinary research (where multiple disciplines work together to tackle common problems) to transdisciplinary research (where disciplinary boundaries fade as researchers work together to address a common problem). ESS consequently has a diverse epistemological framework, adopting fundamental building blocks and methodologies from diverse disciplines to tackle highly complex questions.

The scientific effervescence of the 1980s was linked with the political ambition to do something about global change. Motivated by the Brundtland Report (1987), *Our Common Future*[48], and the growing interest in sustainable development, many actors thought that IGBP should be designed to provide scientific knowledge that was more immediately policy relevant, generating some initial disagreement about the degree of policy relevance that was appropriate for IGBP research[49]. However, a more policy-relevant international research effort would have to wait until the 1990s.

By the end of the 1980s, ESS had emerged as a powerful new scientific endeavour, triggered by the growing recognition of global change and built on the rapid development of interdisciplinary research methods.

[H2]: Going global (1990s-2000s)

The formal launch of IGBP in 1990 and the widespread use of the Bretherton diagram (Figure 2) powered the ongoing development of ESS. Nevertheless, despite the rapidly increasing use of resources and the emerging impacts of climate change, the underlying human drivers of global change, as well as population and community ecology, were not a strong focus of ESS. Motivated by a suite of studies that illustrated the importance and relevance of ecological research to climate change, biodiversity, and sustainability more broadly[50-51], the international research programme DIVERSITAS was created in 1991 to study the loss of, and change in, global biodiversity[52], thus complementing IGBP's research on the functional aspects of terrestrial and marine ecosystems. The quantification of human impacts on the planet from climate change, fixed nitrogen, biodiversity loss and fishery collapses brought the reality of a human dominated planet into focus.[53]

In1996 the International Human Dimensions Programme on Global Environmental Change (IHDP) was founded, providing a global platform for social science research that explored both the human drivers of change to the Earth System and the consequences of a rapidly changing Earth System for human and societal well-being [54]. This global system of international research programmes, including WCRP, IGBP, DIVERSITAS and IHDP, provided "work spaces" for international scientists of different disciplines to come together, which was critical for the development of ESS. In the early 2000s, this more complete suite of global change programmes, along with the emerging concept of sustainability[55], would give birth to sustainability science[56].

In the late 1990s, H-J. Schellnhuber introduced and developed two concepts that were fundamental for ESS[57,58]: the dynamic, co-evolutionary relationship between nature and human civilisation at the planetary scale, and the possibility of catastrophe domains in the co-evolutionary space of the Earth System. The first provided the conceptual framework for fully integrating human dynamics into an Earth System framework (cf. Figure 3). The second introduced the risk that global change may not unfold as a linear change in Earth System functioning, but rather that human pressures could trigger rapid, irreversible shifts of the system into states that would be catastrophic for human well-being. Indeed, the discovery of the stratospheric ozone hole showed that humanity, by luck rather than design, has already narrowly escaped the creation of a catastrophe domain [59].

Over a critical five-year period from 1999 through 2003, the IGBP accelerated its transition from a collection of individual projects to a more integrated ESS programme with the 1999 IGBP Congress being the key to achieving the required integration. Schellnhuber, who had just become the chair of the GAIM task force, challenged the Congress with his call for a deep integration of human activities into ESS and for more emphasis on nonlinear dynamics in the Earth System. The Congress rose to the challenge, launching both the IGBP synthesis project and a major international conference in 2001. The synthesis project resulted in the publication of *Global Change and the Earth System*[60], an integrator of not only the considerable amount of global change research within IGBP but also a vast amount of relevant research carried out elsewhere. It also provided the scientific basis for the

Amsterdam Declaration (Box 1) and emphasised research that would underpin the new concept of the Anthropocene (Box 2).

The 2001conference, “Challenges of a Changing Earth” was truly international, attracting 1400 participants from 105 countries, 62 of which were developing countries. The conference, co-sponsored by the four international global change programmes (IGBP, WCRP, IHDP, DIVERSITAS), introduced the Amsterdam Declaration (Box 1), which arose from the synthesis project, and triggered the formation of the Earth System Science Partnership (ESSP) to connect fundamental ESS with issues of central importance for human well-being: food, water, health and carbon/energy[61]. The emphasis of J. Lubchenco, who became president of the ICSU in 2002, on science for sustainability strengthened the integration of the ESS and global sustainability communities.

This integration led the IGBP to define the term “Earth System” as the suite of interlinked physical, chemical, biological and human processes that cycle (transport and transform) materials and energy in complex dynamic ways within the system[60]. This definition emphasised two points: first that forcings and feedbacks within the system, including biological processes, are as important to it functioning as external drivers; and second that human activities are an integral part of system functioning[62].

The 1990-2015 period was critical for ESS as it moved from a challenging vision to a powerful new science capable of effectively integrating a wide array of disciplines towards understanding our home planet in all its complexity.

[H2] 2015 and beyond

By 2015, ESS was well established, and the time was right for a major institutional restructure built on a higher level of integration. Indeed, IGBP, IHDP and DIVERSITAS were merged in 2015 into the new programme, Future Earth, while WCRP continued along with some IGBP core projects such as IGAC (International Global Atmospheric Chemistry), PAGES (Past Global Changes) and the ESSP Global Carbon Project. Future Earth aims to accelerate the transformation to global sustainability through research and innovation. It builds on the research of the earlier global change programmes but works more closely with the governance and private sectors from the outset to co-design and co-produce new knowledge towards a more sustainable future (www.futureearth.org).

A broad range of research centres now directed their work towards ESS and global sustainability research: for example, the Potsdam Institute for Climate Impact Research (PIK), the US National Center for Atmospheric Research (NCAR), the Stockholm Resilience Centre (SRC), and the International Institute for Applied System Analysis (IIASA). Although universities maintained their traditional discipline based faculties, as the emphasis on interdisciplinarity and global-level studies grew, interdisciplinary ESS programs also emerged in many universities around the world. The revolution in digital communication links these, and many other research bodies, in an expanding global ESS effort.

[H1] ESS tools and approaches

Supporting the evolutionary development of ESS are three interrelated foci that drive science forward: observations of a changing Earth System; computer simulations of system dynamics into the future; and high-level assessments and syntheses that initiate the development of new concepts.

[H2] Observations and experiments

The transdisciplinary research required to understand the Earth System requires past and contemporary changes in the system to be considered at a wide range of spatial (for example, top down and bottom up) and temporal (for example, looking forward and backwards) scales. Perhaps the most iconic 'top-down' observation is the ongoing measurement of atmospheric CO_2 concentration at the Mauna Loa Observatory, Hawaii, which was started in 1958 by C.D. Keeling[63]. The Keeling Curve – as it is commonly known –underpins our understanding of how humans are influencing the climate, depicting continuously increasing CO_2 concentrations[64].

The development of space-based observations at ever higher spatial and temporal resolutions has also revolutionised our ability to repeatedly and consistently observe the Earth System in near real time. Remote sensing systems now monitor a wide range of processes and indicators, including climatic variables, land-cover change, atmospheric composition, the surface ocean and urban development[65-67]. These 'top down' approaches – along with the ability to rapidly process, analyse and visualise large amounts of data - build a compelling, globally coherent picture of the rate and magnitude of changes in the structure and functioning of the Earth System at the planetary level[30].

Bottom-up observations of Earth System processes are challenged by the heterogeneity of the planet but have provided valuable insights into these processes. A classic example is Global Ocean Observations System (GOOS), built around a growing fleet of autonomous platforms such as the Argo floats that continuously collect and transmit ocean data. On land, global networks of long-term sites, such as FLUXNET, measure the fluxes of energy and gases between the land surface and the atmosphere and rooting depths in the soils of major ecosystems[68]. Such process-level studies complement remote sensing observations by providing critical insights into the underlying dynamics that generate the patterns of a changing Earth System observed from space.

Large-scale observational campaigns bring together interdisciplinary teams of researchers to provide a crucial scaling link between local observations and experiments and the planetary level. For example, the NASA Advanced Global Atmospheric Gases Experiment and the NOAA ESRL Global Monitoring Division have tracked how human activities have changed the composition of the atmosphere for over 40 years by tracking not only the increase of greenhouse gases such as CO_2 but also the stabilization of some ozone-depleting gases[69]. The Asian brown cloud study over the Indian subcontinent measured the concentration of atmospheric aerosol particles, their seasonal variation, their atmospheric lifetimes and their transport by atmospheric circulation, important for estimating the risk that the South Asian monsoon could be destabilised by local and regional pollutants[70]. The Large-scale Biosphere-Atmosphere study in the Amazon (LBA) used both ground-based and remote sensing approaches to study the atmosphere-biosphere-hydrosphere dynamics of the Amazon rainforest[71], yielding insights into where a tipping point might lie for the conversion of the forest into a savanna. In the ocean, the GEOSEC programme (1972–1978) studied the distribution of man-made geochemical tracers (from the atmospheric testing of nuclear weapons) in the world's oceans, enabling the estimation the timing and pattern of global cycling of carbon in the oceans[72].

Looking back at the past Earth System is important to understand its present dynamics. The Vostok ice core data[73] marked a major advance by showing the regularity and synchronicity in the temperature–CO_2 relationship through the late Quaternary. Studies of past interglacial periods[74] and the long-term dynamics of the climate system[75], for example, have provided a rich background against which contemporary changes in the Earth System, in both magnitudes and rates, can be analysed. Palaeo studies of the more recent past (tens, hundreds and a few thousand years) are particularly useful in providing insights into future risks. As human forcings drive even more profound changes to the Earth System, time intervals further back in time come into focus as potential analogues, such as the Palaeocene-Eocene Thermal Maximum (PETM) about 56 million years ago, when a rapid release of greenhouse gases triggered a global temperature rise of 5-6°C[76].

Looking ahead, large-scale experiments can explore how parts of the Earth System may respond to future levels of human forcing or interventions. For example, numerous studies have examined the efficacy of iron fertilisation to stimulate oceanic draw-down of CO_2 from the atmosphere as a potential mitigation strategy[77]. On land, Free-Air Carbon dioxide Enrichment (FACE) experiments, in which ecosystems are fumigated over many years with high levels of CO_2, explore ecosystem responses to future atmospheric conditions[78], and ecosystem warming experiments explore responses to the future climate[79]. These, and other similar studies, complement modelling approaches and palaeo studies, enhancing our understanding of how the Earth System could evolve in the coming decades and centuries, and the risks for humanity that changes in the system could bring.

[H2] Modelling the Earth System

Mathematical models are key components of ESS research, starting with conceptual or toy models which elucidate key processes, features or feedbacks in the Earth System, often drawing on the principles of complexity science[80-82]. In the 1960s, for example, simple energy balance models described how the ice-albedo feedback could potentially drive the Earth into an alternative "snowball" stable state[83,84]. The Daisyworld model in the 1980s further showed how feedback processes between life and its environment could lead to global-scale temperature regulation[85].

More complex models of the Earth System — General Circulation Models (GCMs) — have since developed. GCMs are based on the fundamental physics and chemistry of the climate system, including the exchange of energy and materials between the Earth's surface (land, ocean, ice and, increasingly, the biosphere) and the atmosphere[86,87]. They are forced by scenarios of human greenhouse gas and aerosol emissions, providing possible trajectories of the future climate, and the impacts and risks of these trajectories, that can be assessed by the Intergovernmental Panel on Climate Change (IPCC) and used to inform policy and governance. However, there is considerable uncertainty in long-term GCM projections, influenced by parameterisations and omitted or inadequate constraints on feedback processes and interactions between the geosphere and biosphere[88,89]. In addition, GCMs lack human dynamics as an integral, interactive part of the model, instead treating them as an outside force that perturbs the biogeophysical Earth System.

Human dynamics are the domain of Integrated Assessment Models (IAMs), which typically couple economic models of varying complexity to climate models of reduced complexity[90-93]. IAMs have a number of uses, for example: simulating costs of specific climate stabilisation policies, exploring climate risks and uncertainties based on a range of potential policies, identifying optimal policies for a specific climate target, and providing more general insights into feedbacks within the coupled system[94]. In addition, IAMs provide critical information on future greenhouse gas and aerosol emission scenarios, which are used to force the GCM simulations. However, the economic components of IAMs are rarely interactively coupled with GCMs to build a completely integrated ESM. An early exception to this generalisation is the MIT Integrated Global System Model, which coupled a general equilibrium economics model (CGE) to a detailed GCM[95,96].

Arguably the most powerful tools for exploring the complex dynamics of the Earth System, particularly at long time scales, are Earth system Models of Intermediate Complexity (EMIC)[97]. EMICs include the same main processes as GCMs, but have a lower spatial resolution and greater number of parameterised processes, allowing them to run longer timescale simulations that include nonlinear forcings and feedbacks among components of the Earth System. EMICs, for example, can be run at timescales of up to hundreds of thousands of years, allowing the models to be tested against palaeo observations and to explore possible climates of the far future[98,99]. Taken together, GCMs, IAMs and EMICs create powerful ways to explore Earth System dynamics at numerous space and time scales.

The diversity of modelling tools available to the ESS community plays a central role in the research effort. Although best known for their capability to simulate potential future trajectories of the Earth System, models are probably most valuable as knowledge integration tools: they bring our rapidly growing understanding of individual processes into an internally consistent framework; they generate new ideas and hypotheses; and, most importantly, the model–observation interface is the ultimate test of our understanding of how the Earth System works.

[H2] Assessments and syntheses

In addition to observations and modelling, assessments and syntheses have themselves become essential tools within ESS research. Syntheses build new knowledge at a fundamental level, yielding new insights, concepts and understanding that are central to the scientific process. In contrast, the global assessment architecture acts as a broker between the scientific and policy communities, facilitating new directions in research following feedback from the policy sector. Perhaps the best-known example of the latter is the IPCC, where science has clearly influenced policy development, but the policy sector has also prompted new research approaches. For example, the IPCC Special Report on the 1.5°C target, mandated by the policy sector as part of the Paris climate agreement, assessed the significant difference in risks and impacts between the 1.5°C and 2°C Paris targets[100]. The IPCC provided the first targeted assessment of climate change impacts on the ocean and cryosphere[101] and triggered the first quantification of ocean-based mitigation options[102].

A synthesis project was the 2001–2005 Millennium Ecosystem Assessment (MEA), a major effort to document the state of the biosphere, with an emphasis on human-driven pressures and potential future scenarios for the biosphere[103]. That pioneering, interdisciplinary scientific synthesis led directly to the creation of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services[104], which provides broad science-policy interfaces on environment, conservation and sustainability across scales, and has recently published a major assessment following on from the MEA[104].

Syntheses were also an important part of the IGBP and other global change research efforts [60,105-113]. For example, the Global Carbon Project provides an annual carbon budget that integrates our growing knowledge base on the carbon cycle and how it is influenced by human activities[64].

[H1] New concepts arising from ESS

ESS, facilitated by its various tools and approaches, has introduced new concepts and theories that have altered our understanding of the Earth System, particularly the disproportionate role of humanity as a driver of change[53,114,115]. The most influential concept is that of the Anthropocene, introduced by P. Crutzen to describe the new geological epoch in which humans are the primary determinants of biospheric and climatic change (Box 2). The Anthropocene has become an exceptionally powerful unifying concept that places climate change, biodiversity loss, pollution and other environmental issues as well as social issues such as high consumption, growing inequalities and urbanisation within the same framework[116,117]. Importantly, the Anthropocene is building the foundation for a deeper integration of the natural sciences, social sciences and humanities, and contributing to the development of sustainability science through research on the origins of the Anthropocene and its potential future trajectories[118,119].

Tipping elements are a further concept stemming from ESS. They describe important features of the Earth System that are not characterised by linear relationships, but can instead show strongly nonlinear, sometimes irreversible, threshold-abrupt change behaviour[81,120-122]. Tipping elements include important biomes such as the Amazon rainforest and boreal forests, major circulation systems such as the Atlantic Meridional Overturning Circulation, and large ice masses such as the Greenland Ice Sheet[81]. In the latter example, a reinforcing feedback occurs because as the ice sheet melts, its surface lowers into a warmer climate, increasing the melting rate. Beyond a critical point of self-reinforcement, the feedback loop leads to an irreversible loss of the Ice Sheet[81]. More recent research has focussed on the causal coupling between tipping elements – via changes in temperature, precipitation patterns and oceanic and atmospheric circulation – and their potential to form cascades[122-124]. Tipping cascades could provide the dynamical process that drives the transition of the Earth System from one state to another, effectively becoming a planetary-level threshold[125]. Research on tipping elements and cascades highlights the ultimate risks of not only climate change, but also of biosphere degradation and the destabilisation of the Earth System as a whole [126].

A final example is the Planetary Boundaries (PB) framework, which links biophysical understanding of the Earth (states, fluxes, nonlinearities, tipping elements[126]) to the policy and governance communities at the global level[127]. Built around nine processes which collectively describe the state of the Earth System (including climate change, biodiversity loss, ocean acidification and land use change), the PB framework guides the levels of human perturbations that can be absorbed by the Earth System whilst maintaining a stable, Holocene-like state - a ‘safe operating space’ for humanity - the only state that we know for certain can support agriculture, settlements and cities, and complex human societies.

Although the present framework is static in that boundaries are considered in isolation, the next conceptual advance aims to simulate interactions among individual boundaries, integrating the dynamics of the Earth System as a whole into the PB framework.

[H1] Future directions

ESS emerged in the early-mid 20th century from conceptualisations of the Earth that emphasised its systemic nature, such as Vernadsky's observation that life has a strong influence on the chemical and physical properties of Earth; and the Gaia hypothesis of Lovelock and Margulis that Earth functions as a single organism, with self-regulating processes and feedbacks that maintain homeostasis. ESS then developed rapidly, from the 'new science of the Earth' movement in the 1980s to the global research efforts of international programmes such as IGBP. Observational campaigns, Earth System models, and periodic syntheses powered the science forward. In the 21st century the concept of the Anthropocene, which arose in ESS, challenges not only the scientific community, but humanity itself. ESS now faces two critical research challenges:

1. How stable and resilient is the Earth System? Can tipping cascades generate a planetary tipping point? Are there accessible states of the system that would threaten human well-being?

2. How can we better understand the dynamics of human societies? What can ESS contribute to understanding - and perhaps to steering - the integrated geosphere-biosphere-anthroposphere trajectory of the Anthropocene?

The first of these challenges is being addressed by a rapidly increasing effort within the biogeophysical research community on nonlinearities in the Earth System[101,128], tipping point interactions and cascades[123,129], and potential planetary thresholds and state shifts[125]. The second challenge, however, requires a much greater effort as our understanding of the Earth System is still largely constrained to its biogeophysical components. The big challenge is to fully integrate human dynamics, as embodied in the social sciences and humanities, with biophysical dynamics to build a truly unified ESS effort. Figure 3 highlights this challenge, with its inclusion of the anthroposphere as a fully integrated, interactive component of the Earth System, along with the geosphere and biosphere. Forcings and feedbacks among the spheres, included psycho-social feedbacks involving the anthroposphere[130], describe the functioning of the Earth System as a whole.

The human dimensions of ESS must therefore go well beyond economic models (IAMs), and incorporate the deeper human characteristics that capture our core values and how we view our relationship to the rest of the Earth System. Whether these fundamental human characteristics be included in large-scale computational models is difficult to assess, but EMICs may offer the first framework in which this computational 'grand integration' could be attempted.

Other approaches are also useful in exploring the future of the Earth System. The concept of complex *adaptive* systems[80] can build understanding of and simulation tools for the co-evolution of the biosphere and human cultures as social-ecological systems[131]. These approaches can also provide vital guidance for formulating policy and management in the Anthropocene[132]. Although long-ignored by the physical perspectives that have dominated

ESS, understanding these human dynamics is essential for the effective guidance systems required for steering the future trajectory of the system [123,133,134].

Technology will also be important for ESS in the future. The emergence of high-speed computing, digitisation, big data, artificial intelligence and machine learning - the tools of the technosphere[135] - has generated a step change in our ability to sense, process and interpret masses of data in near real-time. This new capability underpins our growing understanding of the key Earth System processes, their interactions and nonlinear behaviours, particularly the the influence of the anthroposphere on the entire system. As these tools develop further, they will allow us to not only learn more about the planet, but also to learn much more about ourselves, our social and governance systems, and our core values and aspirations.

More than technology, however, is required to understand human dynamics. The ESS of the 2020s can draw upon a rapidly expanding portfolio of innovative research and policy ideas to improve our understanding of the anthroposphere. For example, projections of the trajectory of the Earth System – ranging from the biophysical dimensions (for example, climate) to the social sciences and humanities – provide a very wide range of perspectives on the future[90,116,136]. In the policy arena, the earlier Millennium Development Goals, which were strongly human-centric, have now been replaced by the Sustainable Development Goals, which retain a strong human focus on development, equity and other human issues but embed them in a broader Earth System context. One of the most innovative of all new approaches is the Common Home of Humanity, which proposes formal legal recognition of a stable and accommodating state of the Earth System itself (i.e., a Holocene-like state, as defined by the PBs) as the intangible, natural heritage of all humanity[137].

To meet these challenges, ESS must achieve an even deeper integration of the wealth of research tools, approaches and insights that the wide range of research communities offer. Underpinning this broad, global ESS effort is one fundamental, unavoidable truth: Humans are now the dominant force driving the trajectory of the Earth System: we are no longer “a small world on a big planet” but have become “a big world on a small planet” [138].

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Author contributions

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Reviewer information

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Figures:

Figure 1. Timeline illustrating the development of ESS from the mid-20th century. The figure shows the key orgnisations, pivotal papers and figures, and major events that have helped to define and develop Earth System science.

References for Figure 1:
Vernadsky 1926: 2
Lovelock 1972: 32
Bretherton diagram 1986: 4
Brundtland report 1987: 48
Schellnhuber 1999: 58
Vostok ice core 1999: 73
IGBP synthesis 2004: 60
Rockstrom PB 2009: 127
Steffen Hothouse Earth 2018: 125

Figure 2. The NASA Bretherton diagram of the Earth System. The classical simplified depiction of the Earth System and its interactions. The focus is on the interactions between the geosphere and the biosphere, with human forcings represented as an outside force affecting the geosphere-biosphere system. Reproduced, with permission from NASA, from ref 4.

Figure 3. An updated conceptual model of the Earth System. A detailed systems diagram of the Earth System, inspired by the original Bretherton diagram (Figure 2), but with humans (the anthroposphere) as a fully integrative, interacting sphere. The internal dynamics of the anthroposphere are depicted as a production/consumption core driven by energy systems and modulated by human societies, as influenced by their cultures, values, institutions, and knowledge. Interactions between the Anthropocene and the rest of the Earth System are two-way, with human greenhouse gas emissions, resource extraction and pollutants driving impacts that reverberate through the geosphere-biosphere system. Feedbacks to the anthroposphere are also important, including direct impacts of climate change and biosphere degradation but also psycho-social feedbacks from the rest of the Earth System and within the anthroposphere.

Boxes:

[b1] **Box 1: The Amsterdam Declaration**

The Amsterdam declaration, signed by the Chairs of IGBP (Berrien Moore III), IHDP (Arild Underdal), WCRP (Peter Lemke) and DIVERSITAS (Michel Loreau) at the 2001 'Challenges of a Changing Earth' conference, described the key findings of a decade of ESS`. The focus was on recognising the Earth as a single system with its own inherent dynamics and properties at the planetary level, all of which are threatened by human-driven global change. The declaration concluded that:

- The Earth System behaves as a single, self-regulating system comprised of physical, chemical, biological and human components with complex interactions and feedbacks among the component parts.

- Global change is real and it is happening now. Human-driven changes to Earth's land surface, oceans, coasts and atmosphere, and to biological diversity, are equal to some of the great forces of nature in their extent and impact.

- Global change cannot be understood in terms of a simple cause-effect paradigm. Human-driven changes cause multiple, complex effects that cascade through the Earth System.

- Earth System dynamics are characterised by critical thresholds and abrupt changes. Human activities could inadvertently trigger such changes and potentially switch the Earth System to alternative modes of operation that may prove irreversible and less hospitable to humans and other forms of life.

- The nature of changes now occurring simultaneously in the Earth System, as well as their magnitudes and rates of change, are unprecedented. The Earth System is currently operating in a no-analogue state.

On the basis of these insights, the declaration called for a new system of global science, which not only intensified the interdisciplinary approach that had been developed by the four programmes during the previous decade, but also transcended the divide between environment and development. The document ended with a call to the ESS research community to work "…with other sectors of society and across all nations and cultures to meet the challenge of a changing Earth.

Source: Based on ref 60, Box 6.11 (p. 298)

[b2] **Box 2: The Anthropocene**

The term "Anthropocene" was originally introduced by E. Stoermer in the early 1980s but in a specific context in the freshwater limnology research community. It was not until 2000, when the phrase was independently re-introduced by P. Crutzen[139,140], that it spread rapidly throughout the natural and social science communities and the humanities. The Anthropocene as proposed in 2000 had two meanings. In a geological context, Crutzen proposed the Anthropocene as a new epoch to follow the Holocene in the Geological Time Scale (GTS)[140]. In an Earth System context, the Anthropocene was proposed as a very rapid trajectory away from the 11,700-year, relatively stable conditions of the Holocene[60]. The two definitions, although not identical, have much in common[141].

The primary evidence for the Anthropocene were the Great Acceleration graphs, which arose from the IGBP synthesis project and highlight trends in socio-economic and Earth System metrics[60,117,143]. They demonstrated that the rapid exit of the Earth System from the Holocene was directly related to the explosive growth of the human enterprise from the mid-20th century onwards. Although new to the ESS community, the Great Acceleration had already been extensively explored by the historian J. McNeill[144].

In response to Crutzen's (2002) proposal that the Anthropocene be formally included in the GTS[140], the Anthropocene Working Group was established in 2009 by the Subcommission on Quaternary Stratigraphy In 2019, following a decade of research, publications, discussion and robust debate, the AWG formally recommended that: the Anthropocene be treated as a formal chronostratigraphic unit defined by a Global boundary Stratotype Section and Point (GSSP), and the primary guide for the base starting date of the Anthropocene should be a stratigraphic signal around the mid-20th century[145-147].

In the social sciences and humanities, the Anthropocene is viewed as a novel, holistic framing that captures complex human dynamics and their interactions with natural systems[148]. It has generated considerable discussion around the importance of the unequal responsibilities of different countries and people for the Anthropocene[114,149], and highlights not only humanity's geological-scale impacts but its challenge to achieve global sustainability[150].

Fig. 1

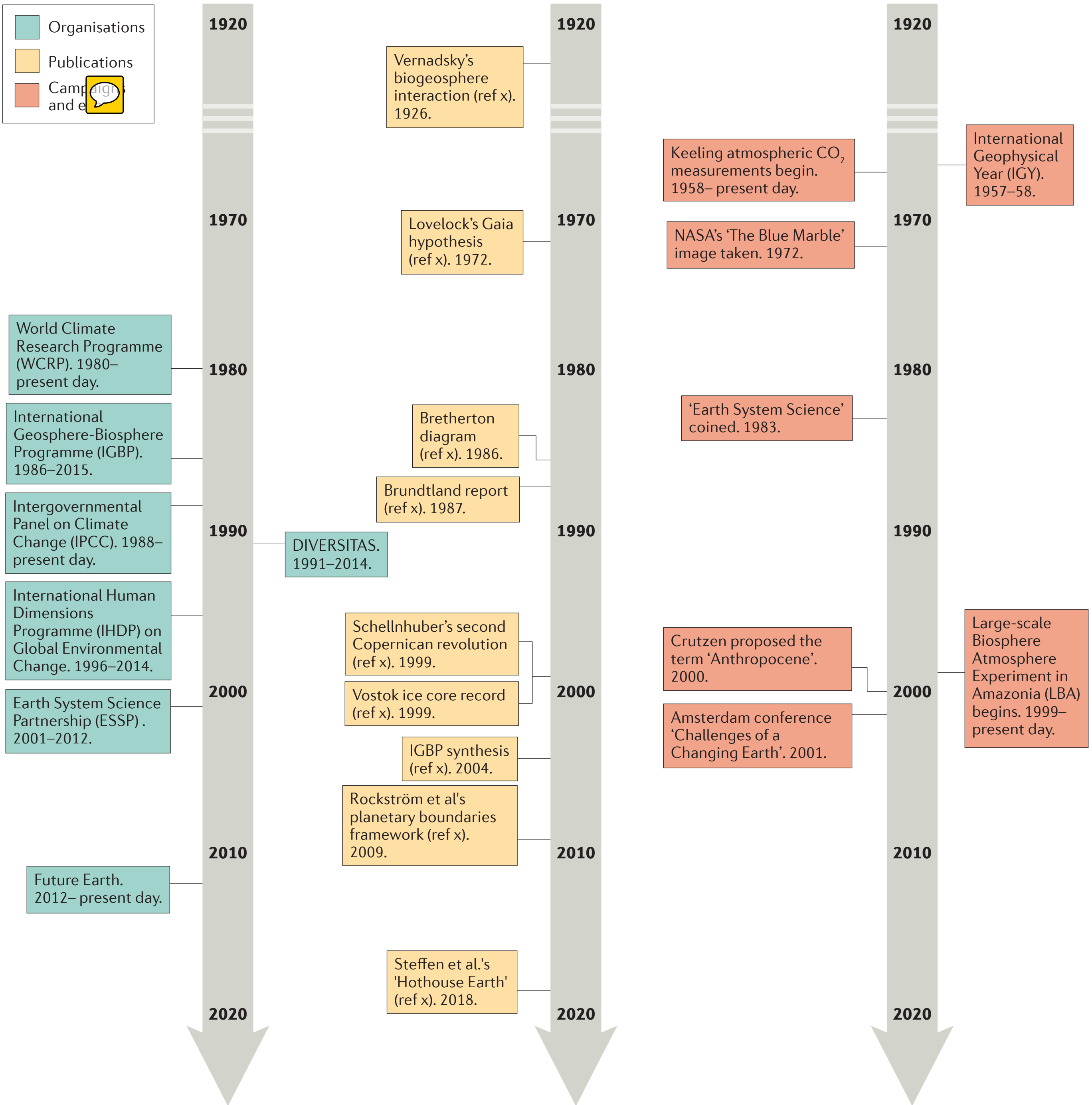

Organisations
Publications
1920
1970
1980
1990
2000
2010
2020
World Climate Research Programme (WCRP). 1980– present day.
International Geosphere-Biosphere Programme (IGBP). 1986–2015.
Intergovernmental Panel on Climate Change (IPCC). 1988– present day.
International Human Dimensions Programme (IHDP) on Global Environmental Change. 1996–2014.
Earth System Science Partnership (ESSP) . 2001–2012.
Future Earth. 2012– present day.
DIVERSITAS. 1991–2014.
Vernadsky's biogeosphere interaction (ref x). 1926.
Lovelock's Gaia hypothesis (ref x). 1972.
Bretherton diagram (ref x). 1986.
Brundtland report (ref x). 1987.
Schellnhuber's second Copernican revolution (ref x). 1999.
Vostok ice core record (ref x). 1999.
IGBP synthesis (ref x). 2004.
Rockström et al's planetary boundaries framework (ref x). 2009.
Steffen et al.'s 'Hothouse Earth' (ref x). 2018.
Keeling atmospheric CO_2 measurements begin. 1958– present day.
NASA's 'The Blue Marble' image taken. 1972.
'Earth System Science' coined. 1983.
Crutzen proposed the term 'Anthropocene'. 2000.
Amsterdam conference 'Challenges of a Changing Earth'. 2001.
International Geophysical Year (IGY). 1957–58.
Large-scale Biosphere Atmosphere Experiment in Amazonia (LBA) begins. 1999– present day.

Fig. 2

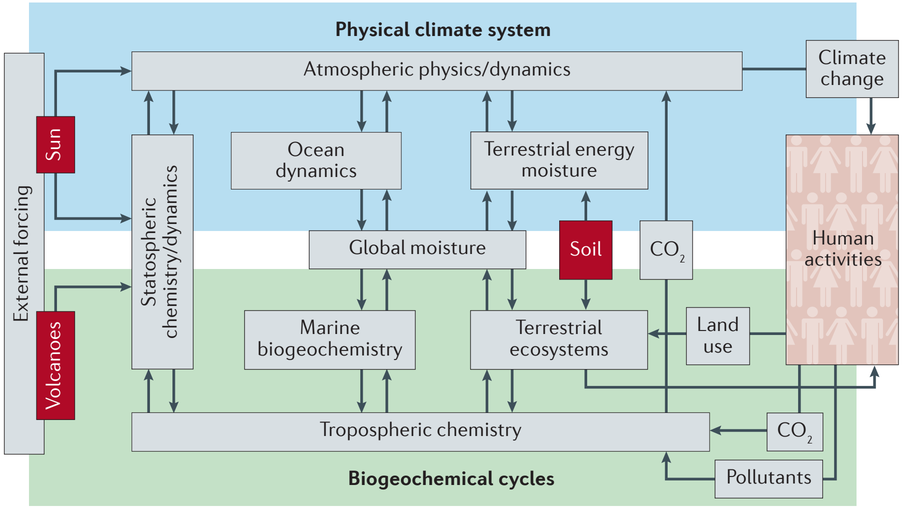

Physical climate system
Atmospheric physics/dynamics
Climate change
External forcing
Sun
Volcanoes
Statospheric chemistry/dynamics
Ocean dynamics
Terrestrial energy moisture
Global moisture
Soil
CO_2
Human activities
Marine biogeochemistry
Terrestrial ecosystems
Land use
Tropospheric chemistry
CO_2
Pollutants
Biogeochemical cycles

Fig. 3

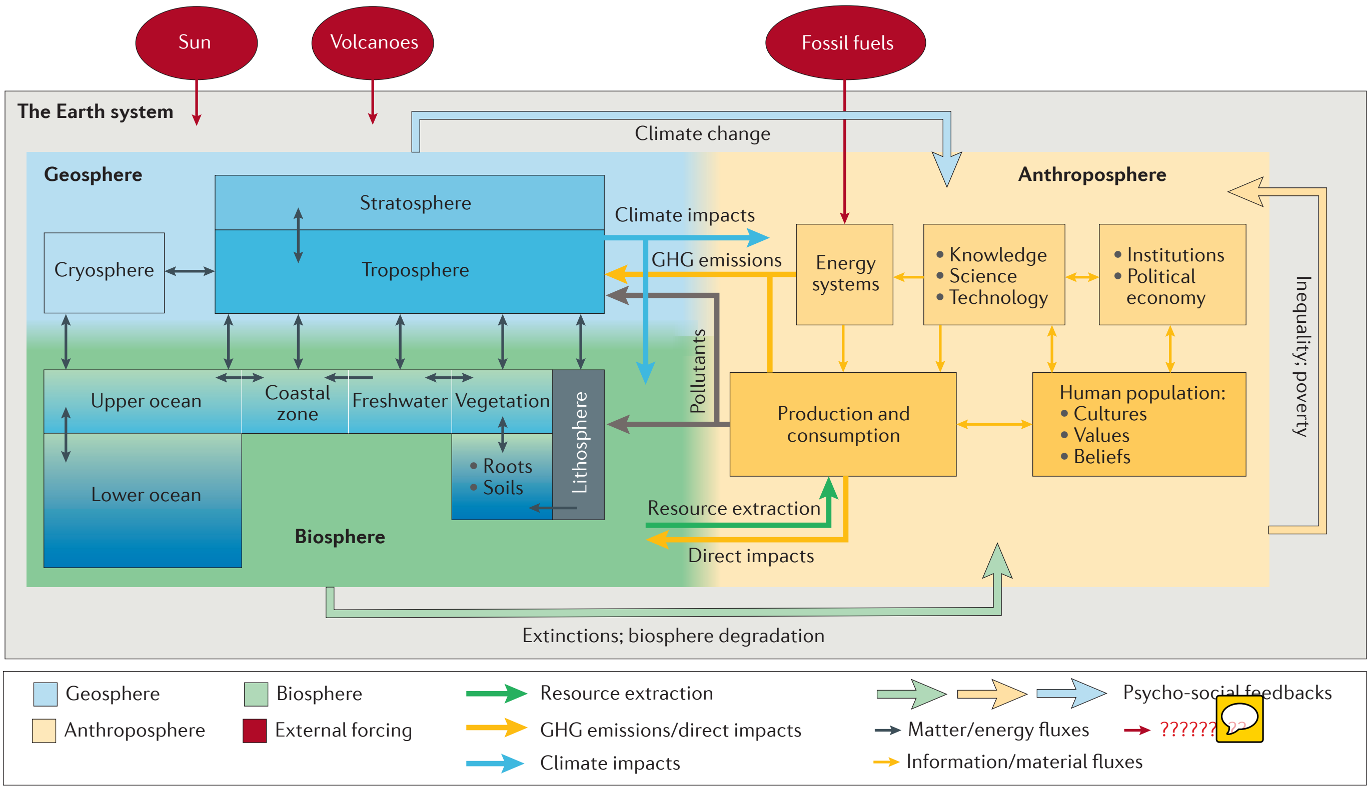
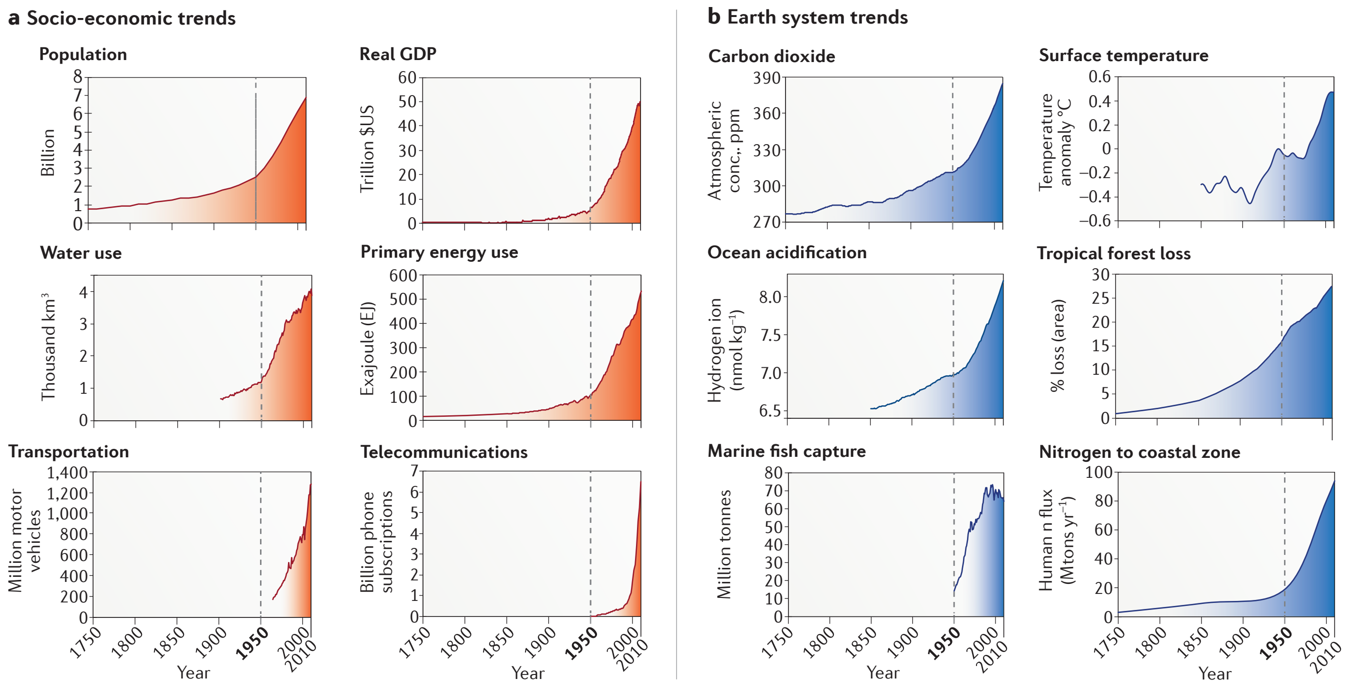

Sun
Volcanoes
Fossil fuels
The Earth system
Climate change
Geosphere
Anthroposphere
Stratosphere
Troposphere
Cryosphere
Climate impacts
GHG emissions
Energy systems
• Knowledge
• Science
• Technology
• Institutions
• Political economy
Inequality; poverty
Pollutants
Upper ocean
Coastal zone
Freshwater
Vegetation
Lithosphere
Lower ocean
• Roots
• Soils
Biosphere
Production and consumption
Human population:
• Cultures
• Values
• Beliefs
Resource extraction
Direct impacts
Extinctions; biosphere degradation
Geosphere
Biosphere
Anthroposphere
External forcing
Resource extraction
GHG emissions/direct impacts
Climate impacts
Psycho-social feedbacks
Matter/energy fluxes
Information/material fluxes
?????

Fig.4


a Socio-economic trends
Population
Billion
Real GDP
Trillion $US
Water use
Thousand km³
Primary energy use
Exajoule (EJ)
Transportation
Million motor vehicles
Telecommunications
Billion phone subscriptions
Year
1750
1800
1850
1900
1950
2000
2010
b Earth system trends
Carbon dioxide
Atmospheric conc., ppm
Surface temperature
Temperature anomaly °C
Ocean acidification
Hydrogen ion (nmol kg⁻¹)
Tropical forest loss
% loss (area)
Marine fish capture
Million tonnes
Nitrogen to coastal zone
Human n flux (Mtons yr⁻¹)

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