Policy design for the Anthropocene

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Today more than ever "Spaceship Earth" is an apt metaphor as we chart the planetary boundaries for a safe planet[1]. Social scientists both analyse why society courts disaster by approaching or even overstepping these boundaries, and we try to design suitable policies to avoid these perils. Since the threats of transgressing planetary boundaries are global, long-run, uncertain and interconnected they must be analysed together to avoid conflicts and take advantage of synergies. To obtain policies that are effective at both international and local levels requires careful analysis of the underlying mechanisms across scientific disciplines and approaches and to take politics into account.

Recent literature on the "Anthropocene" suggests multiple threats to the resilience of the Earth system. Exceeding "planetary boundaries" could lead to rapidly increasing risks of catastrophic and/or irreversible environmental change[2-6]. Acknowledging underlying scientific disagreements and considerable uncertainties, we note there are many articles describing human dominance of the planet[7] and here we take the planetary boundaries as given and focus on the design of policy and governance structures in response to the risks of overstepping them. There are no simple solutions. Design issues are complex and challenging precisely because the threats are global, long-run, inter-connected, uncertain, and potentially irreversible[8]. Nevertheless, we have identified seven guiding principles:

1. Inherent complexities necessitate interdisciplinary collaboration in the design of appropriate policies and governance systems.
2. In order to identify the appropriate strength and type of policy it is important to ascertain how serious the environmental problems are. If possible to measure, this could be given by the distance to the various boundaries.
3. Links across planetary boundaries often necessitate considering two or more of them together—both because policy approaches tackling one boundary may lead to

"ancillary" benefits elsewhere, and because of potential conflicts, where a policy that mitigates human impacts on one dimension exacerbates threats to another.

4. Despite the novelty and complexity of the task, a number of well-known policy instruments exist. The challenge, thus, is not to invent entirely new approaches, but to select and design appropriate policies given specific scientific, societal, and political contexts.
5. Instrument selection depends on a proper diagnosis of the socioeconomic cause(s) underlying the problem, focused on the most significant points of leverage.
6. Effective policy choice and design needs to be based on efficiency, achieving desired outcome at lowest costs, but must also consider "political" criteria such as the distribution of costs and resistance by powerful vested interests.
7. Finally, global problems need policy instruments and agreements that are operational at both international and local levels, to ensure not only efficient outcomes but also effective jurisdiction and governance.

Planetary boundaries and the Anthropocene

The term Anthropocene has been proposed to characterize the current geological epoch[2]. Although its formal stature and starting date are subject to debate[9], it is here sufficient that the term is commonly used to connote the current period when human activity dominates the development of global ecosystems. We use the planetary boundaries framework as a starting point for policy analysis since it suggests a number of clear restrictions and implications. Planetary boundary research attempts to define (i) the key processes that determine the state of the Earth system, and (ii) quantitative boundaries for these processes inside which the risk of triggering a shift to another equilibrium is acceptably low[10]. Not all planetary boundaries are associated with risks of planetary-scale tipping points, but crossing any one increases the risk of catastrophic change. Nine planetary boundaries have been suggested[3] and four of these may already have been transgressed[4]. Some boundaries such as climate change and biosphere integrity, the "sixth mass extinction"[11], have received much attention, but all need more research. Table 1 lists boundaries and their main driving forces. Although the exact positions of planetary boundaries are uncertain, policies are motivated by risk of passing them. Appropriate policy design and stringency level will depend on the distance to each planetary boundary (Figure 1). If a boundary has been transgressed, policy efforts must focus on rapidly returning the system to a safer state. Given the ecological complexities involved, precaution is warranted in policy-making when it concerns drivers leading to possible transgressions of planetary boundaries, particularly in the "uncertainty" or "high risk" zones[12-15].

FIGURE 1

TABLE 1

To date, natural scientists working in this area have focused on characterizing planetary boundaries rather than suggesting "how to manoeuvre within the safe operating space in the quest for global sustainability"[4]. We here focus on policy design. The driving forces behind the unsustainable use of environmental resources, which threaten planetary boundaries, are principally economic. They are caused by growth in population and income but also changes in behaviour and technology. To a significant extent, they are the result of misguided market forces. Designing policies and institutions to deal with these challenges, thus, requires an understanding of how economies work, the relevant trade-offs, and the roles of incentives and political barriers to policy implementation. This is a task for social scientists[16]. Hitherto, the social sciences have delivered some conceptual insights concerning political challenges associated with planetary boundaries[17-20], and proposed institutional architectures for governance and to avoid undesirable environmental problem shifting[21-23]. Here we take a further step by categorizing and discussing specific policy instruments. Although an approach has emerged that treats ecosystems as natural "assets" that are prone to irrevocable change and collapse[14,15,24], only recently have economists begun to appreciate the urgency of applying such methods to the global scale of planetary boundaries[25-26].

Collaboration across a range of disciplines will be crucial to designing effective policies. For simple issues, the process can be sequential: ecologists identify threats; engineers, say, suggest solutions; and social scientists propose effective and efficient policies to encourage achievement of these solutions. However, for the complex, large-scale problems of the Anthropocene, sequential policy formulation is oft inadequate. Researchers and practitioners from different disciplines need to collaborate at each stage of the process in order to ensure a more complete view of possible outcomes, potential policy interventions, and their likely consequences. We attempt to integrate knowledge from multiple fields to synthesize insights and challenges regarding policies for planetary boundaries. We start, in the next section, by explaining the root causes of large-scale environmental problems and how society can design instruments to address them. We then discuss, in turn, coordination between policies at different levels and for different planetary boundaries, spatial and other complexities, political considerations such as vested interests and distributional issues, and the importance of considering socioeconomic dynamics such as demographic change and technical progress.

The Design of Policy Instruments

Most environmental problems—from local smog to transgressions of planetary boundaries—share a common cause: misguided incentives. This key insight from economics is central to the design of effective policies. It is typically linked to so-called "market failures", though it can equally be due to policy failures, if policy makers are ill-informed or corrupted by special interests. Market failures include externalities, public goods, and asymmetric access to information. A common feature is that property rights are not fully assigned; certain resources or actions are "free" from the perspective of the firm or household, though scarce and costly to society. For example, polluters may freely dispose of effluents, leading to eutrophication, or chemicals, causing health hazards and threats to planetary boundaries (such as 6-9 in Table 1). The broad solution is to internalize these societal costs so that each individual decision-maker faces the true costs of his/her actions on society. Polluters need to face this cost to choose appropriate inputs and production technologies. Consumers must also see the full cost of pollution reflected in product prices to make appropriate purchasing decisions. While this principle is simple—only proper incentives lead to appropriate actions—actual policy design and implementation are complicated by factors as varied as ecological complexity of non-linear changes, thresholds, possible irreversibilities, and complex spatial-temporal dynamics on the one hand, and politics on the other. The latter includes factors such as fairness, market structure, lobbying power, asymmetric information, risks, and uncertainties.

High prices of polluting inputs such as oil, rare minerals, or agricultural products not only stimulate efficiency and frugality in use, they also stimulate increased supply. When this supply poses a threat to sustainability, this demands *high* prices for *using* polluting resources but *low* prices for *supplying* them—a wedge between the user and producer prices. This can be achieved most directly by a tax (or tradable permits).

Due to the scale of the human enterprise, planetary-scale environmental problems abound. The interconnectedness of their causes—and their solutions—often leads to environmental problem shifting: Since the 1970s, the local environment in many wealthy countries has improved, sometimes significantly. Yet often the improvement has been achieved at the expense of deterioration elsewhere. That goes for outsourcing of pollution across national borders. It also goes for substituting one pollutant for another. Many countries have addressed smoke pollution from wood fires by switching to fossil-powered thermal stations, one of the main drivers of climate change. Similarly, mitigating climate change using solar technology may increase dependence on rare Earth elements or entirely novel entities. The "theory of second best"[27] provides important lessons for dealing with interacting policies. A key result is that policies that, in isolation, are deemed less efficient than taxes in addressing a particular problem—e.g., technology mandates or performance standards—can become preferable when interactions with other problems are taken into account[28]. More generally, potential shifts across planetary boundaries provide a strong motivation for assessing the effectiveness of different policy instruments on all affected boundaries simultaneously, using the conceptual framework of and, ideally, an actual global "general equilibrium model", a tool that allows the researcher to study the dynamic interactions in an economy rather than being confined to partial analyses or simple rules of thumb. Such an analysis requires careful calibration of interactions and interdependences across planetary boundaries and associated policy instruments.

Meanwhile, policies cannot only focus on incorporating the right price for pollution in individuals' decisions. They must also encourage research, development, and deployment (RD&D) of less polluting technology. The task is to motivate individuals to engage in activities that benefit society, using, for instance, direct subsidies[29]. Table 2 gives a broad overview of available policy instruments, focussing on those implemented at the local and national level. Effective use of policy instruments requires mature governance institutions, while transboundary issues require international coordination, discussed later. Depending on the exact nature of market failures, policy instruments can take one of four general forms: "Pigouvian", which directly affect pollution prices through taxes or subsidies; "Coasian", which directly affect pollution quantities, while allowing for these quantities to be traded; "traditional" regulatory mechanisms that set out rules and quantity limits that cannot be traded; and "indirect" interventions in areas such as finance, law, information access, or societal norms that affect incentives in ways other than through prices, quantities, or direct regulations.

TABLE 2

Table 2 also depicts a further dimension—the all-important distribution of costs. The costs of abating pollution and respecting planetary boundaries can be borne either by the polluters or by society at large, the "victims" of the pollution. The choice may be based on norms, legal considerations, or simply a realistic assessment of what is politically possible given the strengths of public opinion and corporate lobbyism. For each category of policies (columns), the top row shows instruments which assign the pollution or resource rights to the victims of pollution or society at large, and thereby require that the polluters bear the costs; the bottom row lists instruments if the polluters hold these rights and, therefore, society (or pollution victims) must pay for abatement. This is clearest in column 2 where polluters may either have to buy tradable permits or certificates (top), or be given them for free (bottom). Similarly, in column 1, the traditional Pigouvian instrument, taxation, implicitly allocates rights to society. On the opposite end, subsidising polluters to abate essentially gives pollution rights to businesses[29]. Similarly, the instruments listed in columns 3-4 may be more or less generous to the polluters, as shown by the difference between bans, zoning, or other regulations that force industry on the one hand, and permits or even voluntary agreements on the other. There is a similar difference between strict and negligence liability, where the latter gives more rights to the polluter. This dimension of who pays is crucial for perceptions of fairness and—in a world of oft-powerful vested interests, where issues of wealth inequality and environmental degradation are typically intertwined—for political feasibility[30,31].

Examples of effective taxation include taxes on chemicals and fertilizers[32], carbon taxes in Sweden, and fuel taxes in Europe[33]. The latter have increased fuel prices substantially compared to the US, resulting in much lower per capita fuel use[34]. Examples of subsidies include payments for ecosystem services that improve forest cover or reduce pollution of rivers[35]. Perversely, subsidies for coal technologies are still common, indicating the lobbying power of this sector. Taxes and subsidies can also be combined as in deposit-refund schemes or so-called “bonus malus” policies that combine fees on gas-guzzling cars with subsidies to cleaner vehicles[36]. Another large-scale example is refunded emissions fees for Nitrogen oxides in Sweden[37]. Voluntary agreements are extensively used in Japan, where a powerful industry has been successful at avoiding state intervention by “voluntarily” agreeing to abate[38].

Smart instrument design is important, not least to limit costs of policy implementation. While transgressing planetary boundaries can impose large and increasing costs on society[25,38], and while arguments that adopting appropriate policies will be prohibitively costly are likely exaggerated[38-40], policy costs do matter, not least politically. Vested interests seek to minimize their costs so policy makers may face the political necessity of either appeasing polluters by allocating them more rights or decreasing costs by using instruments that promote efficiency. That entails choosing appropriate instruments and implementation strategies to minimize the cost of attaining the desired outcome. The policy challenge is to find the best way to combine, complement and enhance the array of available instruments to tackle the complex, large-scale and often global environmental problems identified by any one planetary boundary or by multiple boundaries in a cost-effective manner, and to avoid lock-in along any one particular path.

Coordinating across geographies and themes

Within any one political jurisdiction, all policy instruments are, at least in principle, available. Global policymaking, which is especially important for those planetary boundaries linked to global pollutants, such as climate change, ocean acidification, and novel entities, must be forged despite the broad absence of governance structures powerful enough to enforce regulations or taxes at a global level. International policy-making, hence, must rely on negotiation and coordination.

The inadequate scope of existing institutions to provide coordinated global action[8,41] is compounded by disparities in income, wealth, and culture[31], as well as strong incentives *not* to cooperate in addressing global pollutants, such as carbon dioxide and ozone. Any international policy-making then depends on a balance of top-down, negotiated agreements on the one hand and bottom-up, local interventions on the other. Both call for starting with small steps using those instruments that are feasible, test their effectiveness, and subsequently gradually increase scope, levels of stringency, and ambition[42]. In some cases, linking across issues (such as multiple planetary boundaries, or other domains like agriculture and trade) can be a viable strategy.

An alternative path forward would be the creation of new institutions capable of harmonizing global decisions—moving toward governance structures that facilitate coordination rather than cooperation[43]. Whatever the approach, it should allow for strengthening (or, occasionally, loosening) of targets over time to account for the distance to planetary boundaries (Figure 1).

Coordination is not only necessary geographically but also thematically, since planetary boundaries are connected across various dimensions. The right combination of immediate implementation strategies, national policies, and international actions should address more than one boundary. Table 3 illustrates one possible approach, by suggesting how these different policies could be combined to tackle multiple planetary boundaries at once.

TABLE 3

As Table 3 shows, the nine planetary boundaries can be regrouped to indicate which have the strongest mutual links, while noting connections to other boundaries. Determining these shared links among boundaries facilitates identification of policies that help mitigate several problems at once, or at least not worsen one while addressing another.

Table 3 also suggests that the physical characteristics that differentiate the key threats to planetary boundaries dictate alternative approaches. For example, the planetary boundaries for climate change and ocean acidification are strongly linked because they share a common main pollutant—carbon dioxide—which, in turn, is linked to global fossil fuel use and land-use changes, in turn drivers for several other boundaries. Thus, an immediate implementation strategy would be to reduce subsidies to fossil fuels, introduce or expand research, development, and deployment policies for renewable energy and establish better policies for land use and freshwater management. For pollutants such as carbon dioxide, the location of pollution is unimportant, pointing to Pigouvian or Coasian approaches that help minimize costs to polluters[37].

Additionally, the global nature of the pollutant identifies carbon dioxide emissions “leakage” as a concern, which occurs when businesses or consumers in one jurisdiction increase pollution in response to abatement elsewhere. Preventing leakage requires international action, hence the need for two-tier policy instruments such as *international* treaties concerning *national* carbon pricing. A similar approach is relevant to control global pollutants threatening the planetary boundaries for atmospheric aerosol loading and novel entities.

Dealing with spatial & ecological complexity

Most threats driving toward the planetary boundaries for biosphere integrity (biodiversity loss), land-system change, freshwater use, and biogeochemical flows arise at the local, national, or regional level. International coordination is desirable to mitigate leakage but especially needed to improve management of key shared resources, such as international river basins, international waters, or major forest biomes, such as the Amazon. Still, overwhelmingly, it is national, local, and regional land-use practices that must change in order to maintain well-functioning ecosystems[16,24]. This points to domestic strategies that can be highly effective despite the lack of international coordination. These include the elimination of agricultural, fishing, mining, forestry and aquaculture subsidies, improved regulation of primary product industries, and water use pricing and regulation, supplemented by a host of additional policies including mining taxes and regulations, hazardous waste regulation, land-fill and waste charges, and new protected areas[44-46].

A key success factor for national, regional, and local policies is to incorporate dynamic aspects of a "socio-ecological" system, such as 1) variation and connectivity, and 2) processes with different time scales and feedback mechanisms. Socio-ecological systems are complex adaptive systems where local interactions give rise to changes at the local, regional, and even global scale. They are challenging to manage because they can exhibit non-marginal changes, looming slow structural changes, spatial and temporal variation, and strategic conscious behaviour among actors[47,48].

Biosphere integrity and climate change, for example, are two complex dynamic issues exhibiting strong connections to each other and to other boundaries[2-4,10]. Staying within the climate boundary requires not only steep reductions in greenhouse-gas emissions but also healthy ecosystems to store carbon. Such ecosystems also prevent biodiversity loss, safeguard freshwater supplies, and provide multiple other linked benefits[10,16]. Management of land system changes must recognize these multiple benefits and the trade-offs that are inevitable when change is induced within a socio-ecological system[24].

Correct pricing of multiple externalities, meanwhile, requires knowledge of both market and ecological interactions[48]. For example, carbon pricing will reduce the pressure on the climate change boundary as well as of ocean acidification and biochemical flows (Figure 2). Yet it will also tend to increase the appeal of biofuels, which may imply negative consequences for boundaries such as land-system change and biosphere integrity. Thus, policy coordination across domains, such as the UN framework conventions charged with climate and biodiversity, is essential to ensure effective stewardship across multiple boundaries, avoiding, for example, that biofuels policies aimed at addressing one boundary exacerbate another.

FIGURE 2

Keeping within planetary boundaries requires that we make better and more cost-effective use of the finite resources and sinks available to us[31]. A better understanding of the spatial distribution of natural capital and the ecosystem goods and services it provides can improve the efficiency and sustainability of resource use[24]. While the spatial distribution of policies to combat ocean acidification is largely irrelevant due to its global nature, the spatial targeting of biodiversity measures is perhaps the single biggest determinant of their success. This becomes more challenging where the distribution of ecosystem services and the beneficiaries of those services are both spatially heterogeneous. Yet despite the obvious importance of the need to target resources in such situations, a failure to consider location is a common hallmark of many environmental policies. Physical, ecological—and spatial—factors are important determinants of value and economics can help articulate such information for decision makers in terms of the social costs and benefits of alternative plans.

Lastly, fast and slow dynamics with reinforcing feedbacks can generate surprising regime shifts. Hence, an optimal policy must manage these complex dynamics to improve efficiency at all system levels. For example, coral growth or shoreline development can lead to regime shifts[49], and responses to prevent these can come too late[13]. Trying to recover after a shift, if possible at all, would require reversing powerful dynamics and thus need massive interventions[50]. Dealing with ecological complexities and possible tipping points calls for rapidly increasing policy stringency, even substantially before actual evidence of an impending threshold or boundary is found. A precautionary policy approach becomes optimal if a regime shift would generate new system dynamics, and human activities can influence that risk, as in multispecies fisheries[15]. Under acute threats of crossing thresholds where social costs rise rapidly, quantity regulation (e.g., permits) is superior to price-based instruments (e.g. taxes)[51], and if the risk of a shift is steeply increasing, a safe standard may be the best policy[14]. Planetary boundaries themselves are examples of such safe standards[3-4,25].

Political economy and fairness

Establishing property rights can be seen as a policy intervention directly aimed at addressing severe market failures. Establishing such rights, however, poses important institutional challenges, especially in countries with weak institutions. Much attention must be paid to equity, justice, and local norms. Meanwhile, property rights do not need to be individual or private. Extensive evidence points to how common property arrangements may work well under certain conditions[52]. Protecting biodiversity, for example, can sometimes be facilitated by institutions that assign and defend clear property rights[53,54], but it also requires engagement by many local stakeholders and active support from public authorities. Rights-based fisheries management provides valuable lessons in how private and societal interests can be better aligned to reduce tensions between industry and regulators[55]. Once assigned, clear property rights should, in principle, allow for the efficient operation of market mechanisms. For example, adopting the legal convention that farmers have the right to pollute waterways provides the basis for "payment-for-ecosystem-services" arrangements, resulting in win-win outcomes where water companies achieve major savings in their treatment costs by funding farmers to reduce agricultural pollution. However, property rights to attributes like biodiversity are notoriously hard to define and enforce, and indigenous people and local farmers are often at the mercy of more powerful commercial interests. Hence, poorly designed privatisation can exacerbate risks to biodiversity[56,57].

Implementation of policies goes well beyond identifying an appropriate intervention. Politics demands overcoming vested interests and oft intense lobbying. For example, fossil fuel interests have clear incentives to portray carbon prices as expensive or regressive[30]. In fact, by stimulating cost-efficient abatement, such prices are generally the cheapest way to satisfy environmental constraints. The true impediment to their implementation is lobbying by the many powerful and wealthy interests that stand to lose from abatement policies[24,34]. If carbon pricing is politically impossible now, transitional policies supporting new technologies (e.g., subsidies for renewable energy or electric vehicles) can induce national engagement and promote counter-lobbies[58]. A particular problem arises when the benefits of pollution are concentrated among a few members of society while the costs are dispersed. Since it is easier to organize lobbies around a concentrated interest, polluters may be able to block a societally advantageous outcome. To counter the oft opaque influence of lobbies, which may occur by way of privileged information, campaign contributions or even bribes, overall transparency is essential, calling for interventions like mandatory and publicly accessible lobbying registers. Here, too, unintended consequences must be taken into account. An outright ban on lobbying, for example, might backfire by inducing increased corruption[59]. This, in turn, can have several negative consequences, including reduced abatement investments[60]. A clear challenge is designing policy instruments to minimize political resistance both by lobby groups and by voters, who might dislike the distributional impacts of a policy. While no panacea, one way forward is via policy instruments specifically designed to raise revenue that can then be used to increase political support[61,62]. For example, some European green tax reforms have reduced voters' tax burden elsewhere, via reductions in other taxes. Subsidy removal must be accompanied by compensating measures. Similarly, refunded emissions payment systems have made higher charges on industrial nitrous oxide emissions politically feasible[37]. Table 2 classifies each of these policy instruments as belonging to the intermediate category.

Technological change & population dynamics

New technologies are a powerful engine of socioeconomic transformation, but they themselves can cause transgression of planetary boundaries by rendering resources accessible to massive exploitation. Much depends on *which* technologies are improved[63]. The RD&D behind technological change is a purposeful human activity; its intensity and direction respond to incentives[64]. Policies, therefore, can and must be designed to both stimulate innovation in technologies that support sustainable growth and weaken the incentives to develop technologies that threaten it[65].

Since fossil fuels have become a key source of energy, technical improvements have led to continuous productivity increases in their extraction, processing, and use. These technological improvements have facilitated a sufficient increase in supply for the relative cost of energy to be stagnant or even falling despite increasing demand. Hence, fossil fuel consumption has increased in parallel with economic activity. Raising fossil fuel prices is a way to break this link and provide incentives for energy saving technologies, an effect powerfully illustrated by the innovations that followed the oil crisis in the 1970s. It can also be seen by the differences in fossil fuel use of countries with divergent tax policies[66].

New technologies for exploration often make previously unrecoverable, even unknown, reserves exploitable. When such exploitation poses a threat to sustainability, subsidies to develop green technologies are likely a key component of policies for sustainability. However, such instruments on their own are generally insufficient. They need to be combined with policies that directly deal with the pollution or resource use in order to reduce the incentives for the type of technological innovation that threatens sustainability[31,63]. Policy-induced green technical progress can make it less costly and hence more likely for countries to impose pollutant pricing and other policies. A telling example is the Montreal Protocol on substances that deplete the ozone layer, which provided the international governance structure within which countries used specific pieces of legislation to phase out and ban the use of halocarbons. Its success was due, in large part, to the development of alternative technologies. Overall, a balanced mix of policy instruments for abatement and investment in clean technologies is often the best recipe for dealing with global environmental threats. Addressing ocean acidification or climate change requires both carbon pricing to reduce emissions cost-effectively in the near term and RD&D subsidies or feed-in tariffs to drive innovation and diffusion of advanced technologies for deeper emissions reductions in the future[67]. Counteracting agricultural, forestry or marine exploitations that threaten biodiversity (and, more generally, boundaries 3-5) necessitate international agreements on a suite of policies that restrain current exploitation but also research into novel future technologies that can radically reduce the pressure of the underlying societal processes on the ecosystems concerned (see Table 3).

Developing countries have their own priorities and, to make green policies acceptable, they must allow for alleviation of chronic poverty and demographic challenges[31]. Development agencies and local governments must use policies that promote green transformation while respecting the interests of the poor, for example, by encouraging local resource management. One impetus for change may come from growing popular demand for a cleaner environment, in particular in major cities. Energy and transport policies that deal with local health and environmental issues are often conducive to several planetary boundaries, including biosphere integrity, climate change, novel entities, and aerosols. While regulations may initially be selected, some of the more flexible instruments highlighted in Table 2 have the advantage of both saving money and raising revenues to address funding and distributional challenges.

Demographic changes, meanwhile, pose a significant challenge to any implementation strategy. Policies must be adaptable to a world with a population increase of several billion people striving for higher standards of living. While not typically part of an environmental policy portfolio, increasing reproductive choice via women's educational opportunities and access to family planning services is an essential component of avoiding threats to planetary boundaries[68]. Limiting population growth alone will not suffice, but demographic changes must not be ignored in policy conversations about the Anthropocene. Satisfying fundamental needs is possible—including the economic growth urgently needed for poverty alleviation—but only if economic activity is steered by strong policy instruments toward sectors and technologies that avoid threats to planetary boundaries.

Concluding thoughts

The range of topics discussed has been broad but is far from exhaustive. Developing policies for the multitude of complex issues related to planetary boundaries is a task both vast and urgent. Formulating policies that adequately address all boundaries is daunting, but the urgency is such that we cannot let complexity be an excuse for inaction. We have argued here that policies are available, but policy design needs to deal with a multitude of geographic levels, interconnected boundaries, and spatial, ecological and socio-political complexities. Doing so requires interdisciplinary collaboration both among academics and practitioners at all levels of policy intervention. This Perspective can only discuss the broad directions of this large undertaking but hopes to inspire a new field to deal with this vital predicament.

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The authors declare no competing financial interests.

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ILLUSTRATIONS: Figures and Tables

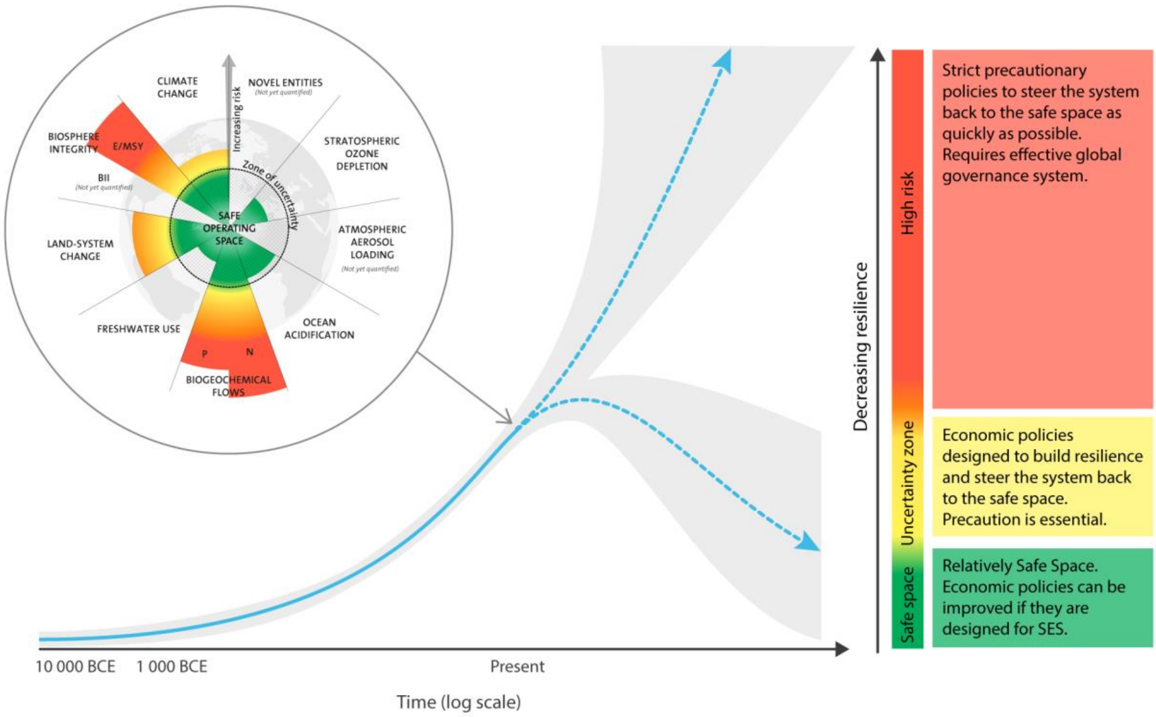

Figure 1 Planetary boundaries, tipping points and policies

Transgressing planetary boundaries increases the risk that the Earth System trajectory (blue solid curve) crosses a planetary tipping point (bifurcation in trajectory). Avoiding the tipping point (lower dashed line) means remaining in Holocene-like conditions. ('Stabilized Earth' trajectory in ref. 10). Crossing the tipping point (higher dashed line) leads to very different conditions, e.g. a 'Hothouse Earth' trajectory, implying serious disruptions to ecosystems and society. Policies in the right column help avoid the tipping point and achieve a 'Stabilized Earth' trajectory. However, significant loss of resilience when multiple boundaries are crossed increases the risk of crossing the planetary tipping point and thus decreases the degrees of freedom available to policy makers (from green to red). BII, Biodiversity Intactness Index; E/MSY, extinctions per million species per year. P Phosphorous, N Nitrogen; SES Socio-Ecological System.

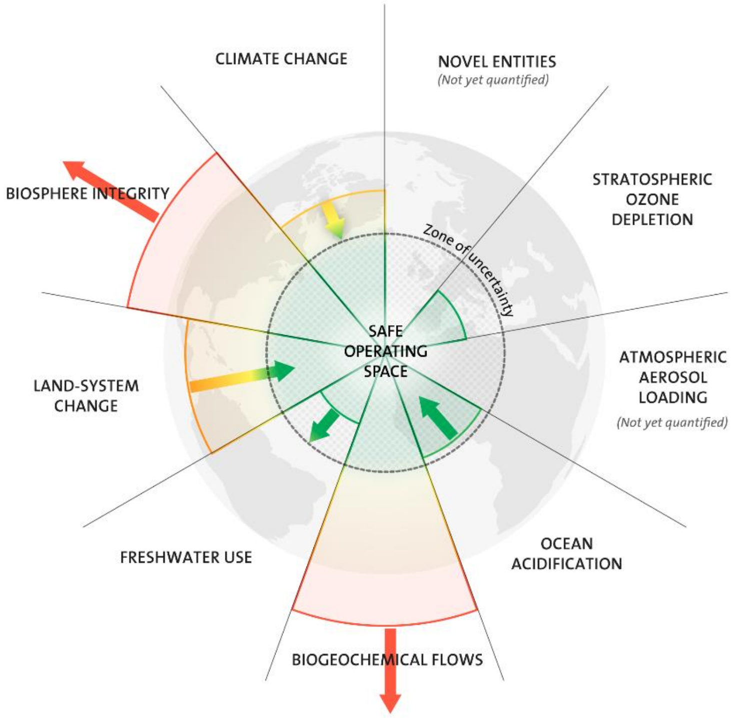

Figure 2 Planetary Boundaries and Policy Trade-offs

The arrows illustrate the principle of trade-offs involving a policy aiming to reduce stress on one planetary boundary (as an example, we take increased forestry to reduce climate change) that may have side effects (positive or negative) on other boundaries (e.g., biosphere integrity, land-system change, freshwater use and biochemical flows). The arrows give an approximate illustration of a possible effect with respect to current conditions[4], where green is safe, yellow increasing risk and red high risk.

Table 1 Planetary boundaries, their drivers and the main sectors of the economy concerned.

PLANETARY BOUNDARY	MAIN DRIVING FORCE	MAIN SECTORS, ACTIVITIES AND INPUTS ASSOCIATED WITH THE DRIVERS
1. Climate change	Concentration of CO_2, N_20, CH_4, CFCs in the atmosphere.	Fossil fuels in energy and transport, industry, cement, agriculture and forestry, livestock.
2. Ocean acidification	Dissolve CO_2 in the oceans.	All above activities emitting CO_2.
3. Biosphere integrity	Land and resource use, ecosystem degradation, climate change.	Forestry, agriculture, fisheries, urban expansion, tourism.
4. Land system change	Change in cropland & forest area.	Agriculture, forestry, urban expansion.
5. Freshwater use	Use of freshwater from rivers, lakes, reservoirs and groundwater.	Agriculture, some industries, domestic use.
6. Novel entities	Human introduced chemicals and other engineered material and organisms.	Research and development sectors linked to plastics, pharmaceuticals, and pesticides. Fossil fuels. Petrochemistry.
7. Stratospheric ozone depletion	Concentration of CFCs and HCFCs in the atmosphere.	Air conditioning, refrigeration, antiperspirants.
8. Biogeochemical flows	Fertilizers, waste flows from industrial activities.	Agriculture, mining, (chemical) industry.
9. Aerosols	Emissions of black carbon, organic carbon, sulfates, nitrates.	Heating, cooking, transportation, industry or forest fires. Fossil fuels.

Table 2 Policy instruments by type and by concept of rights over nature.

Rights primarily allocated to	"Pigouvian" (price-based)	"Coasian" (rights-based)	Regulatory	Legal/Information /Finance
Victims	Taxes Charges, fees, tariff	Tradable permits/quotas (auctioned)	Bans	Strict liability Stricter financial regulation
	Deposit-refund Refunded charge	(Green) certificate Common property resource management	Zoning Performance/technology standards	Negligence liability Financial Regulation Public participation
Polluter	Subsidies	Tradable permits/quotas (allocated freely)	Permits	Voluntary agreements Information disclosure

Most instruments here apply to both consumption- and production-based, negative externalities. Positive, learning-by-doing spillovers require their own sets of interventions via technology standards, patent law, etc that can be categorized in an analogous manner.

Table 3 Planetary Boundaries: Policy instruments at national/international level and implementation strategies

Due to their physical characteristics, multiple planetary boundaries can be safeguarded through the right combination of immediate implementation strategies, additional national policies and international actions. Numbering as in Table 1. The first two boundaries are connected through the role of carbon dioxide. There are close ties between 3,4 and 5 through land use, and all three are also affected by climate change. We also group 6 plus 7 because ozone depletion is caused by novel chemicals.

PLANETARY BOUNDARY	IMMEDIATE IMPLEMENTATION STRATEGIES	ADDITIONAL NATIONAL STRATEGIES	INTERNATIONAL ACTION
1 Climate change 2 Ocean acidification [Linked to 3-5, 7-9]	Eliminate fossil fuel subsidies. Facilitate breakthrough low-carbon and energy efficiency technologies through research and development (R&D) subsidies and infrastructure investment (e.g., smart grids, improved transmission and distribution).	Carbon pricing through taxes and/or tradable permits. Carbon emission regulations. Technology policies for reducing all greenhouse gases (GHG). Carbon sequestration incentives.	Implementation of Paris Agreement pledges. Negotiation of additional agreements and more stringent pledges as follow-up to Paris Agreement. Climate finance for mitigation in developing countries.
3 Biosphere integrity 4 Land system change 5 Freshwater use [Linked to 1, 2, 8]	Reduction and rationalization of agricultural, fishing, mining, forestry and aquaculture subsidies. Improved regulation of primary product industries. Water use pricing and regulation.	Market-based instruments for reducing agricultural and water pollution. Water markets and trading. Taxes/regulation for hazardous waste & mining. Landfill and waste charges. New protected areas. Strengthen property rights.	Regional and international agreements and coordination necessary for management of transboundary water, land and marine resources (e.g., internationally shared marine reserves & water, major river basins, deep sea resources or forest biomes).
6 Novel entities 7 Stratospheric ozone depletion [Linked to 1-3, 9]	Speed up and strengthen the US TSCA, EU REACH and similar liability and authorization legislation. Improve information on risks.	Technology policies to reduce use of harmful entities. Taxes and regulations to control over-use	Improved coordination and additional agreements for novel entities (e.g., using the Montreal Protocol on ozone regulation as a model).
8 Biogeochemical flows [Linked to 1, 3-4]	Similar to 3-5.	Planning with catchment areas. Empower local users.	Some coordination to reduce large-scale and shared impacts.
9 Atmospheric aerosol loading [Linked to 1, 6]	Improved information on impacts and risks. Monitoring, reduction and control of forest fires.	Technology policies, taxes and regulation to control over-use and pollution (e.g., from vehicles, industry, fires).	Coordination to reduce large-scale and trans-boundary pollution (e.g. from forest fires, industrial pollution).