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Managing the climate commons at the ecology-behaviour-economics nexus

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Sustainably managing coupled ecological-economic systems requires not only an understanding of the environmental factors that affect them, but also knowledge of the interactions and feedback cycles that operate between resource dynamics and activities attributable to human intervention. The socioeconomic dynamics, in turn, call for an investigation of the behavioural drivers behind human action. We argue that a multidisciplinary approach is needed in order to tackle the increasingly pressing and intertwined environmental challenges faced by modern societies. Academic contributions to climate change policy have been constrained by methodological and terminological differences, so we discuss how programs aimed at cross-disciplinary education and involvement in governance may help to unlock scholars' potential to propose new solutions.

Dealing with climate change requires enhanced integration between ecology and economics, but such partnerships are also essential in addressing a wide range of challenges in achieving a sustainable future[1]. Many recipes for preserving the Earth's climate from dangerous change have been proposed. The delayed damaging effect of greenhouse gas emissions (GHGs) and their transboundary nature (independently of the source, all emissions increase the world's stock of concentrations) aggravate the problem. Hence prescriptions for addressing the global external cost arising from human activity are bound to be multifaceted and to rely on various instruments and methodologies. Traditional theories of collective action have until recently shed a pessimistic light on the prospects of self-organisation in limiting the use of communal resources to a sustainable level. This is in part due to Hardin's 'tragedy of the commons', whose policy implication was to rely on coercion in the form of either privatization or government intervention[2,3]. Although more recent work has demonstrated that under a wide range of circumstances, communities are able to self-restrain and avoid resource overexploitation[4], global cooperation at the scale required to reduce emissions and decarbonise the economy may be difficult to sustain without sanctions. In fact, the present lack of a supranational institution for regulating global carbon emissions sets the stage for free-riding, i.e. individual countries have an incentive to delay curbing emissions and rely on the mitigation efforts of others.

Does this gloomy picture change when we shift attention from gradual global warming to abrupt changes in the climate system, i.e. drastic and potentially irreversible ecological shifts? The threat of an impending low-probability, high-impact disaster might be imagined to be a stimulus to mitigation efforts. One might think that humanity would rise to the challenge of a rapid transition to a carbon-free economy once alerted by early warning signals such as the climate system has been providing us; but that has not been the case. Inaction remains the norm, and delaying the economic costs of mitigation, while engaging in repeated rounds of negotiations without addressing the root causes of global warming, appears to be the norm. Even with agreement, 'solutions' might not be achievable. We may have already passed a critical threshold, such as the 350 parts per million by volume atmospheric CO_2 required to safeguard polar ice sheets[5]. Even if we haven't already crossed a planetary boundary for dangerous climatic change, we must still be able to identify future early warning signals and collectively agree on large-scale action in the face of incentives for individual countries to free-ride. Lastly, should a global agreement be struck in response to a perceived threat, uncertainty regarding the amount of time and the degree of effort required to reverse course and contain atmospheric CO_2 within a safe operating space will persist. Clearly, we need to develop and implement a framework for global cooperative action that is robust to structural scientific uncertainties (as well as to uncertainty about societal responses to mitigation policies). Collective action can resolve commons problems at smaller scales[4,6]; the challenge is in extending those principles to achieve enforceable agreements among nations towards a sustainable future[7].

Threshold uncertainty surfaces in the latest IPCC's Summary for Policymakers[8] . The authors state that:

"There is high confidence that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (low confidence) but less than about 4°C (medium confidence) global mean warming with respect to pre-industrial."

In sum, obstacles to climate cooperation are compounded by deep scientific uncertainty concerning the timing and magnitude of climate change impacts[9,10]. Avoiding a tipping point leading to catastrophic climate events is much more difficult when its location is hard to pinpoint[11], a feature that cannot be disregarded, given the recently reported plurality of thresholds for abrupt climate change[5,12,13]. Furthermore, the link between emissions and climate change is also subject to error propagation[14], meaning that we cannot attribute with certainty an emergency to increases in climate radiative forcing. Yet, the evidence that long-lived global warming can be attributed to anthropogenic causes is strong[8].

How can science inform the debate on reaching an international agreement to keep temperature increases within acceptable boundaries? More broadly, what type of science-society interface is conducive to better management of global environmental commons? A multidisciplinary effort is needed to address policy-relevant problems and explore appropriate economic instruments to deal with present-day environmental concerns[15]. The time is ripe for economists and ecologists, along with other physical and social scientists, to join effort to analyse individual and collective behaviour with the lens that is most appropriate given the research question at hand, rather than within disciplinary boundaries[16]. The insular nature of the social sciences and their especially tenuous academic link with ecology and Earth sciences (Fig. 1), have hindered the study of coupled social-ecological systems. Progress has been made in bridging the gaps[1,16-19], but collaborations across the sciences need to identify better the intertwined drivers of successful commons' management.

Academic insularity is particularly troublesome for problems, such as climatic change, that are characterized by deep (often-irreducible) uncertainty. In similar circumstances of uncertainty, clinical evidence suggests that human judgment is subject to biases and limited diagnostic and predictive ability[20]. Reaching across the disciplines involved in complex problems may mitigate such problems and help remove obstacles to cooperation arising from misunderstandings and lack of dialogue (Table 1). On the other hand, disciplinary focus has traditionally been the norm due to at least two reasons: lower entry costs to researchers (once a set of skills has been acquired, it can be usefully used in other projects, without the same need to invest in new methods or in vocabulary for communicating with academics trained in other disciplines); and, partly for the same reasons, a reward system favouring work that is confined within disciplines (for instance, it is easier to assess the value of the latter, as a norm of acceptability is more likely to have been established than in the case of research than spans multiple subjects). Our aim here is to identify some theoretical tools that have effectively bridged gaps across the behavioural sciences, as well as opportunities for further integration.

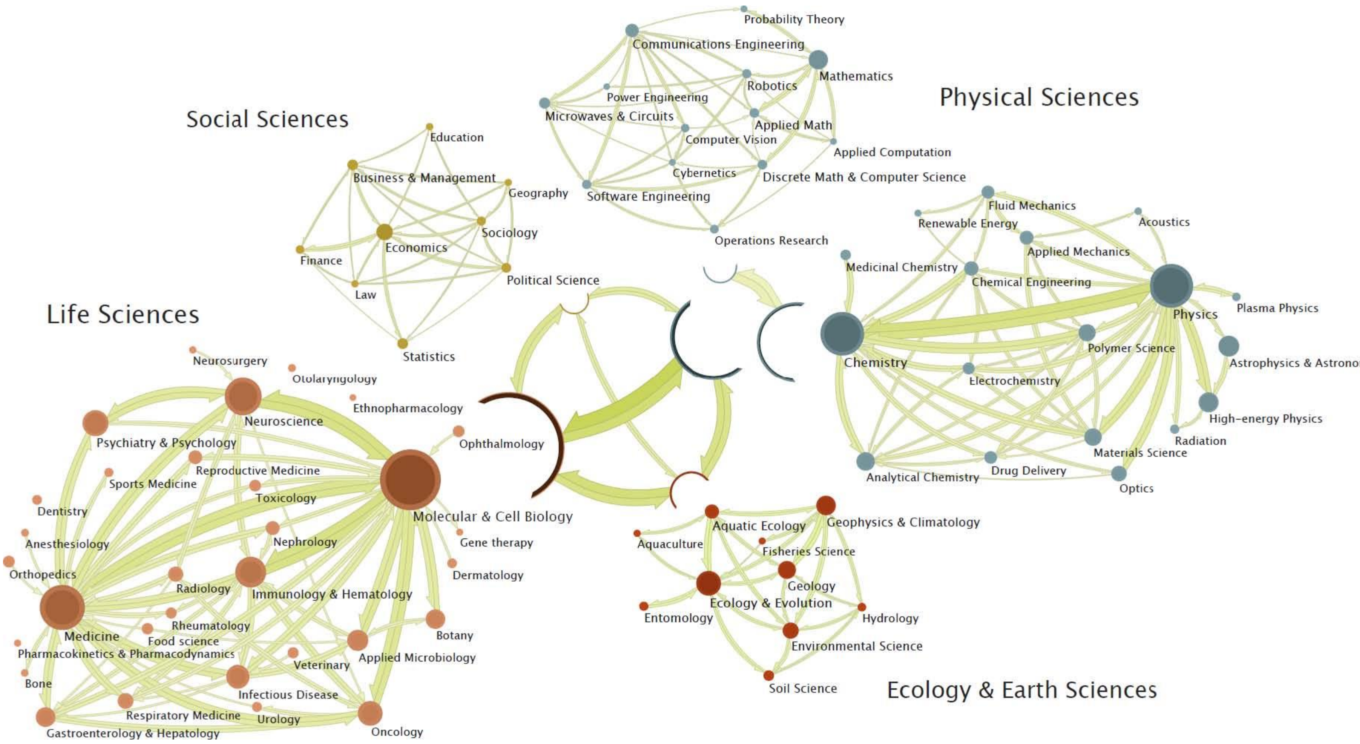

Figure 1: Insular Social Sciences. Ref. [99]'s hierarchical map of science, which splits scholarship by clustering 9.2 million journal citations from the 2007 Thomson-Reuters Journal Citation Report into four disciplines. Arrows indicate citation traffic for the most important links, with larger, darker arrows indicating higher citation volume.

Common ground

Ecology is concerned with complexity and non-equilibrium dynamics, and economic tools allow investigation of the anthropogenic impact on the environment beyond simple representative-agent models. "Evolutionary game theory has been credited for redefining how institutions are integrated into the analysis, behavioural economics for shedding light on how rationality is treated and experimental economics for changing the way economists think about empirical work"[21]. The examples below show that while traditions are different (environmental economics is grounded in the theory of optimization and externalities, whereas ecology tends to focus on systems as adaptive and path-dependent), the methods are compatible[22]. Similarly, the different orientations to efficiency vs. stability are not mutually exclusive, and can often be reconciled. Indeed, the similar trade-offs between current performance and adaptability, exploitation and exploration, etc., are central themes across disciplines, from behavioural economics to the theory of life-history evolution, to consideration of the fundamental roles of mutation and recombination in evolution[23].

At the core, ecological systems are in many ways special cases of economic systems, and vice versa, with both featuring competition for resources, parasitism, exploitation and cooperation. Ecological and economic systems alike self-organize through selection among and transformational dynamics of the units that make them up, from individuals to larger ensembles. It is not surprising, therefore, that the methods developed in one context can elucidate patterns and processes in the other; conversely, restricting attention to either the economic or the environmental system alone will inevitably bias the analysis by disregarding feedbacks between the two [24]. As Shogren and Crocker[25] put it, in the context of species survival, "Assessing the risk to species and setting a minimum acceptable probability of survival are economic as well as biological problems."

Evolutionary dynamics

A prime example of overlap and complementarity is found in the literature on the evolution of cooperation[26], in which methodology and approaches have flowed freely across disciplinary boundaries. For instance, adaptive schemes such as replicator dynamics have been used both by economists and biologists to study common-pool resources[27,28]. While equilibrium analysis is a principal tool for economists, evolutionary economics emphasizes non-equilibrium trajectories, without assuming that efficiency can be assessed in the absence of distributional metrics[29]. Here, we use the term 'evolution' to include a variety of mechanisms of change, whether genetic or behavioural in nature. The methods of game theory, which have their roots in economics[30], have been adapted and developed in the evolutionary theory literature[31], and subsequently made their way back into economics in modified form. The synergies from such cross-fertilization should be a model for other approaches.

Dynamical systems, game theory and tipping points

Dynamical systems theory is the standard starting point for modelling temporal changes in ecological and economic systems[32]. Management approaches rely on the choice of functions or parameters in such models to optimize performance characteristics. However, when interacting agents are involved, optimization approaches give way to game theory, which can be used to analyse cooperation in global commons such as the climate, both theoretically and experimentally (e.g., in prisoner's dilemma and public goods games[11,33]. Furthermore, the application of game theory to international environmental agreements has provided significant insights with respect to the provision of transboundary public goods, such as abatement of GHGs[34.35].

Attention to tipping points in dynamical systems enjoyed wide attention thanks to the popular book by Gladwell[36], but the topic has long attracted scientific interest, from the successes of the theory of phase transitions in physics[37] to the less successful program of catastrophe theory[38,39]. More recent work on critical transitions in a wide variety of dynamical systems addresses problems of fundamental importance across ecological and economic systems. This work holds the promise of providing methodology to anticipate transitions as well as to design principles that can help avoiding undesirable regime shifts, though again care must be exercised to avoid overreaching [40-42]. Lakes can flip from oligotrophic to eutrophic states, vegetation systems from grasslands to forests, and financial systems from growth to recession or depression[43,44]. Analogous transitions can also undermine (or enhance) regimes of cooperation regarding common-pool resources, presenting challenges for the management of the commons[27,45,46]. This is a promising area for future collaboration between natural and social scientists.

Agent-based models

Traditional methods rely heavily on analytical techniques, and usually on numerical solutions. In most cases, however, what can be done analytically is limited to models of reduced dimensionality, and such analyses must be complemented by simulations and agent-based modelling. These are useful adjuncts to parsimonious analytical efforts that, while illuminating in the analysis of basic incentives, may not be best suited to investigate more complex interactions. The ability of an agent to win trust and reciprocate the efforts of others is key to explaining cooperation. In the context of climate cooperation, Elinor Ostrom observed that agents at levels below the nation-state can also be important to international climate change policy [47]. She and Vincent Ostrom suggested that the trust gained and lessons learned by many parallel actions, by agents at various scales ('polycentric governance'), are more likely to bring about progress than is waiting for a comprehensive international treaty among states[48].

The techniques of agent-based models hold tremendous potential for investigating the interactions among large numbers of agents, and for the development of rules for scaling from the microscopic details of individual interactions to the emergent properties of large ensembles. Building models with huge numbers of free parameters increases the uncertainty in prediction, making essential the development of approaches for achieving an appropriate 'statistical mechanics' for the interactions among large numbers of agents. Traditionally, in fluid mechanics for example, moment closure and related methods are useful in this regard[49], and newer methods are available when moment closure is too difficult[50]; to date, such approaches have received little attention in the social sciences (but see ref. 51).

The problem of scale and emergence

An essential area of complementarity between economics and ecology involves sustainable development and the physical dimensions of the economy[52]. At the core of sustainability issues are problems of distribution - of physical and biological properties across ecosystems and biomes, and of resource availability across individuals, nations, and time. These challenges raise issues of organizational, temporal and spatial scale that cut across disciplines. Ecologists are concerned with scale, and emergent features of population dynamics and ecosystem robustness and resilience[53,54]. These concepts are implicit in the distinctions between micro- and macroeconomics, have been widely explored in some contexts in economics[55], have inspired new subfields such as the 'new economic geography', and are drawing increasing attention in the economic literature[56]. Ecological models have long been incorporated in the theory of renewable resources in environmental economics[57,58], and recently for the analysis of exhaustible resources[59,60]. These involve issues of scaling from individual incentives to system-wide consequences and back. Increasingly, linkages between local and global drivers need to be forecasted to account for such interdependencies. In the words of Barnosky and colleagues, "to minimize biological surprises that would adversely impact humanity, it is essential to improve biological forecasting by anticipating critical transitions that can emerge on a planetary scale and understanding how such global forcings cause local changes"[61]. We next review some recent academic advances that may help with the task.

Recent trends

Modern science is breaking strict disciplinary boundaries. The last decades have witnessed what some have termed the complexity revolution in economics[21,62]; it is asserted[62] that "modern economics can no longer usefully be described as 'neoclassical', but is much better described as complexity economics", which "embraces rather than assumes away the complexities of social interaction." Below we present some examples of progress along these lines that is already under way, focusing on tools and concepts that, while more mainstream in ecology and Earth sciences, have only recently surfaced in the social sciences.

The economy as a complex system

Economics has lately devoted much attention to threshold effects in environmental responses to human activities. Much can be learned from ecology and the literature on regime shifts and early warning mechanisms[40,41,46,61]. Furthermore, the concept of robustness or resilience is highly relevant for ecological dynamics[63], economy-environment dynamics[64], as well as networked (interdependent) socioeconomic systems[65,66]. Progress has also been made towards finding unifying processes in biology. Brown's metabolic theory strives to present a unified theory of "biological processing of energy and materials" in ecosystems, enabling evaluation of anthropogenic pressure on the diversity of organisms, and more generally of the connection between the complex function played by individuals embedded in ecosystems and the drivers of individuals' functioning (such as temperature, size and abundance of nutrients)[67]. Metabolic theory inspired work in subjects as diverse as societal metabolism and urban metabolism, evidence that the once common paradigm of assuming away complexity in theoretical modelling in order to achieve analytical rigour needs not be the only one. Increased computing power at more affordable prices also means that fewer compromises need now be made when modelling complex systems.

Recent cross-disciplinary efforts have started to tackle the complex interactions between human system and environmental systems. Measuring the ecosystem services provided by different resources is a complex task [68], contributing to the under-pricing and unsustainable use of resources such as fresh water and the atmosphere as a carbon sink. To illustrate the need for dialogue among experts, let's briefly consider practical attempts to evaluate policies while accounting for coupled ecosystem and economic dynamics. These fall under the 'environmental impact assessment' label, a "management tool which has the ultimate objective of providing decision-makers with an indication of the likely consequences of their decisions relating to new projects"[69]. Increased public discussion and participation of different sub-national stakeholders are attractive features of this tool, but several drawbacks hinder its applicability. An important one is striking equilibrium between environmental and economic goals. Given the financial implications of environmental impact assessments that are frequently linked to the licensing of permits, a structured approach for weighing the costs and benefits of a project along both the environmental and social dimensions is needed to avoid the corruption (or disproportionate industry lobbying). Evidence from India suggests that when such balanced assessments are not in place, public discussions may be steered towards the least controversial criterion, and thus overlook potential reasons for aborting a project[70]. Accounting for the complexity of social and ecological systems, and the linkages between the two, could help mitigate this problem and contribute to more objective project evaluations across different criteria.

Behavioural and experimental methods

In the absence of enforcement mechanisms, conventional game theory using one-shot or repeated interactions predicts that the temptation to defect leads individuals to resource overuse, hence justifying Hardin's prediction of the tragedy of the commons. In many situations, however, there is more to human behaviour than selfishness: findings from behavioural and experimental economics, as well as from neuroscience have argued that human choice is a social phenomenon[71], and 'behavioural failures' are widespread[72]. Kahneman's research[73] suggests that social norms and framing of options significantly influence behaviour, with significant repercussions for human cooperation and resource exploitation. In particular, ethics and prosociality are increasingly relevant for ecologists and economists, as environmental sustainability is intrinsically linked to ethical considerations[74].

Diffusion through networks

Behaviours and technologies diffuse through social interactions, with adoption by one agent increasing the likelihood that others will follow suit. Network analysis can be useful in determining how the adoption and the speed of diffusion of green technologies or behaviours depend on social connections: mutually reinforcing choices can lead to accelerating diffusion[75,76]. Under these circumstances innovations may spread in a similar fashion to epidemics. Network topology has profound implications for the outcome of diffusion. Chung and colleagues, for instance, find that a norm of social sanction towards defectors who overharvest a shared resource is destabilised in loosely connected networks, whereas it supports cooperation in networks with high degree of connectedness[77]. Connectedness can also have adverse effects, as contagion can lead to mounting systemic risk, and the spread of destabilizing features through over-connected networks[69].

Cooperation across scales

In light of the lack of progress by the international community in curbing GHG emissions, the question of whether local climate governance may be less riddled with barriers to cooperation than international agreements has been posed both in policy and academic spheres. Specifically, the hope is that loosely coordinated unilateral action by governments and industries would more efficiently deliver emissions reductions[78]: Will the prospect of acting as a leader in green technologies fuel a global 'green race' among industries and countries[79]? Should policy-makers whose goal is to steer their economies away from fossil fuels then focus on subsidies to nascent green markets, rather than on achieving efficiency via taxation? The analysis of the interaction between bottom-up drivers of environmental management and the top-down incentives arising from global architectures to curb GHG emissions has just begun[47,80,81], and largely remains an empirical question. Behavioural and natural scientists could profitably pool their respective expertise and develop a cross-disciplinary theory backed by cross-scale data, in order to shed light on how cooperation unfolds when mutually influenced local and global drivers are considered.

Consider the debate in economics over the drivers of income variation across space, namely "the poorly understood fact that countries in temperate and colder regions have higher per capita output than most low-latitude and high-temperature regions"[82]. Nordhaus notes that much of the economic growth literature has been polarised in one of two camps, which either focus on geography or national institutions. The narrow focus on these two competing explanations, by failing to investigate the complex interaction between environment, wealth and norms, loses sight of important related questions pertaining to the evolution of institutions. For instance, why do we observe so much institutional variation across space? Models of group formation, such as those used in evolutionary biology[83], augmented with environmental traits (e.g. climatic favourability), could be used to study the evolution of cooperative institutions under different combinations of environmental stressors and wealth availability. Again, seemingly unrelated disciplines provide inspirational clues for broadening the picture to include relevant insights. Social psychologist Van de Vliert has moved away from the view that either institutions or geography explain income distribution, by suggesting that trust and other cooperation-inducing cultural traits result from the combination of climate and affluence[84].

	Increasing degree of interdisciplinarity →		
	Economics	Economics+ Evolutionary Biology	Economics+ Evolutionary Biology+ Other Behavioural Sciences
Anticipated human responses to policy	Allocation of resources through the (carbon) price signal will efficiently reduce global emissions	Path dependency and myopic behaviour may lead to suboptimal mitigation trajectories. Punishment mechanisms are needed	Financial incentives may discourage cooperative behaviour by crowding out perceptions of moral duty towards the common good. Fairness and ethics are as important as monetary incentives
Anticipated ecosystem responses to human activity	Ecological feedbacks are largely ignored in standard modelling, which focuses on strategic incentives and rational actors	Increased greenhouse gas concentrations will alter several drivers of ecosystem processes (e.g. temperature and precipitation),with complex ecosystem responses	The coupling of social and ecological processes implies that we should further consider the effects of the changing environment on individual and societal organisation. These include adaptation and the emergence of new norms

Table 1: Reducing bias through disciplinary harmonization. Differences in anticipated effects of a stylised policy proposal to combat climate change through emission trading, when progressively breaking down research silos.

Forward look

Human socio-economic systems and the ecosystems on which they are dependent cannot be analysed in isolation, due to the inherent complexities and feedback processes operating across systems[24]. Furthermore, many of these processes exhibit nonlinearities; this means that ignoring feedback cycles and focusing on more tractable linear dynamics (as has traditionally been the case in economics modelling) may miss important and potentially irreversible patterns[44,85]. Some of the limitations of theoretical ecology and economics have been resolved within their respective frameworks, often by incorporating relevant insights from the other discipline. Focusing on the management of global environmental commons, we have identified topics where the bridging of the gap between the two scholarly foci has already begun, as well as areas that call for further integration.

Climate change research is illustrative of the need for greater cross-disciplinary collaborations, because an assessment of the net economic and ecological damages occurring from alternative trajectories of anthropogenic interference with the climate system requires creatively merging insights and methodologies often developed autonomously. Consider solar radiation management, a geoengineering method aimed at reducing climate change. The impacts of solar radiation management pertain to both the ecological effects of injecting sulphate aerosols into the stratosphere and the strategic incentives for action. Ecosystem impacts include direct effects on the Earth's radiation balance and key ecosystem drivers (e.g. reduced global temperature change compared to business-as-usual GHG emissions, decreased stratospheric ozone concentration and changed precipitation patterns), as well as indirect effects[86]. Ecosystem responses of oceanic, freshwater and terrestrial ecosystems will be spatially heterogeneous and to a large extent unpredictable, creating potential winners and losers from large-scale geoengineering and redistribution issues[87,88]. A comprehensive treatment of this technology needs therefore to look at countries' economic incentives for (possibly unilateral) deployment, and the associated distributional, governance and legitimacy issues [89].

Our view is that a deep understanding of the economic stakes and incentives is a necessary but insufficient condition to foster cooperation and avoid wasting resources[90]. Given the meagre achievements of repeated rounds of climate negotiations in limiting emissions, it is time for a strategic rethink. Although we do not claim that academia can provide on its own the solutions to the problem of international climate cooperation (academic collaborations can also be seen as necessary requirements), integrating insights from across the disciplines can help in at least two ways. First, there is mounting evidence that individuals, and hence countries, base decisions on a wider set of determinants than efficiency, as prescribed by the rational actor model in neoclassical economics[71-73]. By proposing solutions that draw from and integrate creatively insights from a broad range of disciplines, academics can produce more accurate predictions of human responses to environmental policies such as those aimed at curbing emissions. Secondly, the complexity inherent in global environmental change requires that the proposed policies reflect an understanding of the linkages between social and ecological dynamics. A narrow focus on either in isolation will result in biased policies that fail to capture important feedbacks between human activity and ecosystems' response.

We have focused on how scientific dialogue between economists and ecologists, and more broadly between behavioural and natural scientists, may contribute to propose new ways of fostering climate cooperation (see Table 1 for an example of the additional insights that interdisciplinary may contribute to policy problems such as the implications of a market for tradable CO2 emission permits). Naturally, we see the need for an effort at drawing from many more disciplines, with obvious candidates from the behavioural sciences being psychology and philosophy. Sandel highlights the risks of crowding out nonmarket norms of restraint when introducing market incentives such as tradable pollution rights for firms or carbon offsets for individuals[91]; ignoring ethical and psychological drivers may thus undermine the effectiveness of a policy seeking economic efficiency[92]. It has been argued that, similarly to what happened with the integration of astronomy, chemistry and physics, different behavioural disciplines should be unified to avoid the current incompatibility in modelling human behaviour. Gintis[93] notes that "Each of the behavioral disciplines contributes strongly to understanding human behavior. Taken separately and at face value, however, they offer partial, conflicting, and incompatible models. [...] Yet, recent theoretical and empirical developments have created the conditions for rendering coherent the areas of overlap of the various behavioral disciplines."

Such unification is in its infancy, but it as a necessary step to increase the policy relevance of academic work on environmental problems such as climate change, as well as to balance the analysis away from its current bias towards the rational actor model. To foster interdisciplinary thinking and reducing disciplinary 'firewalls', education should tackle the challenge early on, by actively engaging college students in the topic of climate change. McCright and colleagues[15] suggest that problem-based learning is well suited to climate change education, and may be instrumental in promoting mental models that are appropriate to understand nonlinear, stochastic and dynamic climate phenomena. They stress the importance of enhancing multiple literacies (e.g. scientific, quantitative and climatic) of all students by developing curricula targeted to college students in science, technology, engineering and mathematics (STEM disciplines) as well as to non-STEM majors, "who also will need to make informed decisions about climate change as citizen stakeholders".

Hands-on education and dissemination projects aimed at improving climate governance, by broadening stakeholder involvement in policy consultation and implementation, have recently sprung up around the world. The EU funded project LIFE: Environment and Climate Action has a budget for the period 2014-2020 of about €3.5 billion, of which almost a third is allocated to the sub-programme for climate action, which tackles the above objective through one of three priority areas, titled Climate Governance and Information [https://www.eutrainingsite.com/2014-2020.php?id=129#euf]. In the US, similar projects involving either interdisciplinary research on climate change education or its dissemination have been promoted by the National Aeronautics and Space Administration, the National Science Foundation and the National Oceanic and Atmospheric Administration's Communications and Education Program[15]. At present, a large fraction of the important insights generated through academic research never trickles through to governance due to the limited academic incentives for greater policy involvement. Yet, projects such as the ones mentioned above are milestones for promoting direct involvement of faculty and students in policy formation and implementation, with great potential to favour exchange between academia and government bodies.

What can we learn from the surveyed cross-disciplinary attempts at education and policy-relevant knowledge generation, with regard to handling complex social-ecological problems? Focusing on what is arguably the most challenging problem ever faced by humanity, sustaining ambitious international climate cooperation, we have attempted to identify ways in which academia could assist governance. Academics play a potentially instrumental role both as educators and as researchers. However, this potential is still underused due to academic insularity, both relative to the government and across the disciplines (Fig. 1). Policy relevance can be improved by working on the former: pooling expertise and reaching across disciplinary boundaries is well worth the effort, as it will be instrumental in advancing practical solutions to the increasingly complex management of the global environmental commons. To this end, the field of ecological economics needs to further mature beyond the exchange of methods between natural and social scientists[94]. Increased computational power by affordable modern computers presents a great opportunity for tackling the added complexities of modelling coupled social-ecological systems, but to exploit it scholars must engage in the far-reaching collaborations needed to support model interaction across disciplines[95].

A number of issues top the list of those where substantive integrative partnerships will be fruitful. Given the spatial and temporal repercussions of global environmental problems, intra-generational equity concerns require that we deal with the distributional aspects of utility, and confront the challenge of aggregation across people and across nations. Inter-generational equity issues raise the spectre of discounting, where the issues are not just what rate to use but whether hyperbolic discounting is more appropriate[96]. Moreover, once objective goals or guides for negotiation are agreed upon, we still need to decide how decisions about the future will be made democratically, and how cooperation can be reached in addressing the commons issues, and attaining a sustainable future for humanity. The analytical methods that must be developed cross disciplines, blending techniques from evolutionary theory[31,94], theory of voting[97], collective decision-making [4], optimization [90], and game theory[30,98]. Linguistic and methodological barriers pose challenges to maintaining rigour in research collaborations. Yet the academic rewards and potential for more grounded and influential policy work should serve as an incentive to rise to the challenge. The time is ripe and there is momentum to build on.

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Author Contributions

A. T. jointly conceived the study with S. A. L.; both authors collected and reviewed the literature and contributed to the ideas presented. A. T. wrote the first draft of the manuscript. A. T. and S. A. L. wrote and edited parts of the manuscript.