Ethics, Policy & Environment

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cepe21

When Ecology Needs Economics and Economics Needs Ecology: Interdisciplinary Exchange during the Anthropocene

S. Andrew Inkpen & C. Tyler DesRoches

ETHICS, POLICY & ENVIRONMENT
https://doi.org/10.1080/21550085.2020.1848182

When Ecology Needs Economics and Economics Needs Ecology: Interdisciplinary Exchange during the Anthropocene

S. Andrew Inkpen[a] and C. Tyler DesRoches[b]

[a]Mount Allison University, Sackville, NS, Canada; [b]Arizona State University, Tempe, AZ, USA

ABSTRACT
Evidence that humans play a dominant role in most ecosystems forces scientists to confront systems that contain factors transgressing traditional disciplinary boundaries. However, it is an open question whether this state of affairs should encourage interdisciplinary exchange or integration. With two case studies, we show that exchange between ecologists and economists is preferable, for epistemological and policy-oriented reasons, to their acting independently. We call this "exchange gain." Our case studies show that theoretical exchanges can be less disruptive to current theory than commonly thought. Valuable interdisciplinary exchange does not necessarily require disciplinary breakdown.

KEYWORDS
Interdisciplinary Science; Anthropocene; Ecology; Economics; Environmental Policy

1. Introduction

A multidisciplinary group of scholars within the International Commission on Stratigraphy – known as the Anthropocene Working Group – recently recommended the Anthropocene as a new geological epoch (Voosen, 2016; Zalasiewicz et al., 2017). This new epoch signals the growing recognition that we humans are a major geological and environmental force on par with natural forces, and has, for obvious reasons, proven to be a hotbed for discussion and debate well beyond geology (Bonneuil & Fressoz, 2015; Corlett, 2015; Purdy, 2015; Steffen et al., 2007; Thomas 2013). One thread in this discussion focuses on interdisciplinarity: recognizing that human and natural factors are inseparable forces scholars to confront problems and systems that contain factors that transgress traditional disciplinary boundaries (Bostic, 2016; Bostic & Howey, 2017; Castree, 2014; Ellis et al., 2016; Inkpen & DesRoches, 2019; Ledford, 2015; Rylance, 2015). This is especially so for mainstream ecology and economics. Until recently, economics has by and large explicitly ignored the 'natural' environment, while ecology has largely focused on it exclusively (Dasgupta, 2010; Martin et al., 2012; O'Neill & Kahn, 2000). One consequence of the Anthropocene consensus is that the distinction between human and natural systems is no longer firm. Human-natural coupled systems are not exceptions, but the new norm (Liu et al., 2007a, 2007b; Pickett et al., 2005). Economics and ecology, deliberately separated in the nineteenth-century on the basis of different research objects and objectives, are now

CONTACT C. Tyler DesRoches tyler.desroches@asu.edu School of Sustainability, Arizona State University, Wrigley Hall, 800 Cady Mall #108, Tempe, AZ 85281, USA

rethinking their separation, as evidenced by growing interdisciplinary research programs, such as ecological economics.[1]

There is a growing body of literature in philosophy of science examining interdisciplinarity, often through the lens of 'integration.' This literature has its origins in the Unity of Science movement (Kitcher, 1999; Oppenheim & Putnam, 1958), but has been the subject of sustained and systematic treatment since Lindley Darden and Nancy Maull's classic paper about 'interfield theories' (Darden & Maull, 1977). This literature is now accelerating, perhaps as a result of the increasing interdisciplinary nature of contemporary science itself and the need to understand the conditions under which interdisciplinarity will be successful (Brigandt, 2013; De Grandis & Efstathiou, 2016; Grüne-Yanoff & Maki, 2014; MacLeod, 2018; Morgan & Grüne-Yanoff, 2013). This literature has focused on a broad range of issues, including: traditional philosophical problems, such as reductionism and incommensurability (Longino, 2013; Mitchell, 2003); the conceptual, methodological, and theoretical entities that are exchanged between disciplines (Rice & Smart, 2011); the types of exchanges that occur between disciplines (Grüne-Yanoff et al., 2014); whether interdisciplinary exchange has been productive or detrimental (Love & Lugar, 2013; Mäki 2013; Plutynski, 2013); and the reasons for interdisciplinary integration and exchange, whether ontological, methodological, or epistemological (Brigandt, 2013; Mitchell, 2009).

In this paper, we would like to put this literature into conversation with the growing recognition of the Anthropocene, since the latter is taken to signal the need for interdisciplinarity across the natural sciences, social sciences, and humanities (Bonneuil & Fressoz, 2015). As Bostic and Howey (2017) state,

> Mindful of the predominantly earth sciences audience of *Anthropocene* [. . .] we aim to highlight the critical importance and value of collaboration with the full range of liberal arts disciplines – from the humanities to the arts to the social sciences – in studying the Anthropocene. Whereas geoscientists may rightly lay claim to debating the pros and cons of a new formally recognized geological epoch, other disciplines necessarily come into play when we broaden inquiry to understanding the profound shifts the Anthropocene presents for human and natural history. (2017, 105)

Without insisting that embracing the Anthropocene is imperative, our question is the following: what are the implications, if any, for interdisciplinary exchange between ecology and economics that arise from a world that contains a mixture of anthropogenic and non-anthropogenic factors?

We argue, first, that the collapse of the distinction between natural processes and societal processes inherent in the Anthropocene consensus has signaled the causal entanglement of the objects traditionally studied by ecologists and economists. Drawing on recent literature about types of idealization in science, we claim that this can be construed as the breakdown of a disciplinary idealization: that ecology is to ignore anthropogenic factors and economics, in general, is to ignore the non-anthropogenic factors. This suggests that impediments to interdisciplinarity can sometimes be helpfully construed as idealizations. Focusing on two case studies – one demonstrating ecology's need of economics, and the other showing economics' need of ecology – we argue that excluding anthropogenic factors from ecological models and non-anthropogenic factors from economic models lessens their predictive success, which ultimately has implications for environmental policy. This mutual dependence rests on the fact that the target systems for both disciplines include anthropogenic and non-anthropogenic factors and, as we will show, excluding one set of factors is not an innocuous idealization. Finally, we argue that interactions between scientists should be epistemically informed, that is, based on evidence of greater predictive success or explanatory power, rather than merely informed by disciplinary affiliation and commitments. This may seem like an indisputable claim, but historically – at least in ecology and economics, as we indicate below and return to in the conclusion – interactions have been structured by what is perceived as the proper objects of study for each discipline and what factors are to be ignored in model-building (see also: DesRoches et al., 2019; Inkpen, 2017a, 2017b). Our normative claim – that scientific interactions should be informed by reasonably expected predictive or explanatory payoffs – reinforces Huutoniemi et al.'s descriptive claim that successful interdisciplinary research is often epistemologically oriented, that is, researchers that are sympathetic to interdisciplinary exchange consider 'boundary crossing as necessary for more profound understanding or more comprehensive explanations' (Huutoniemi et al., 2010, p. 85).

The recent literature on interdisciplinarity in the philosophy of science has focused on enumerating the conditions underwriting the possibility and success of interdisciplinary integration and exchange. However, we ask the following question: what makes interdisciplinarity worth advancing? We argue that the recognition that so-called human-natural-coupled systems are the new norm should encourage exchanges between ecology and economics. In the two cases provided below, exchange between these disciplines is epistemologically preferable to their acting independently. Building on the recent work of Miles MacLeod and Michiru Nagatsu (2016), we call this *exchange gain*. Moreover, our cases demonstrate that theoretical exchanges can be less disruptive to current theory than might be expected. This goes against a common set of claims – as described in MacLeod and Nagatsu (2018) – that interdisciplinarity should involve significant integration between disciplines: integration that is transformative for those disciplines, or involves a significant breakdown of disciplinary practices, or involves the creation of a novel interdiscipline. We claim that interdisciplinary exchange brings epistemological advantages without requiring a substantial breakdown of disciplinary boundaries or practices.

Our article proceeds as follows. Section 2 explains the Anthropocene and its implications for interdisciplinary research. It also lays out our argument explicitly. Section 3 summarizes our contribution to the recent literature about interdisciplinarity. Sections 4 and 5 provide case studies of interdisciplinary exchanges between ecology and economics, respectively. Section 6 concludes.

2. Interdisciplinary Exchange in the Age of Humans

Imagine a world in which ecology and economics get on quite well without one another. This is a world that is made up of relatively independent human and natural systems: one set of systems, the object of ecology, consists of non-anthropogenic or 'natural' factors; another set, the object of economics, consist of anthropogenic or human factors. In such a tidy world, these sciences, when operating effectively, make successful predictions and prescribe policy interventions without the need for interdisciplinary exchange.

Throughout much of the twentieth-century this imaginary world seems to have been implicitly assumed. As ecologist Robert O'Neill and economist James Kahn wrote in 2000:

> the current paradigm in ecology considers humans not as a keystone species [a dominant species on which other species within an ecosystem depend] but as an external disturbance on the "natural" ecosystem. [. . .] The problem with this approach is that human beings are, in fact, another biotic species within the ecosystem and not an external influence.
>
> But the artificial isolation of humans from their ecosystem is not due only to the ecologists' paradigm. In the economic paradigm as well, human society, with all of its self-organization and self-regulatory activity, is represented as a separate "system." The ecosystem is viewed as external to society, providing goods and services, unoccupied territory in which to expand, and assimilative capacity to handle by-products. [. . .] The ecological paradigm isolates human activity in a box labeled "disturbances." The economic paradigm, in turn, isolates ecosystem dynamics in a box labeled "externalities." (O'Neill & Kahn, 2000, p. 333)

Of course, this imaginary world is just that, a fiction. The real world is messy. Strictly speaking, there is no longer any part of the earth's surface that remains completely detached from human technologies (Bensaude-Vincent and Newman 2007; Mckibben, 1990; Vogel, 2015; Wapner, 2010). By the late 1990s, it was estimated that up to one-half of the earth's land surface was transformed by human action (Vitousek et al., 1997). Today, roughly 75% of ice-free land on earth has been transformed by agriculture and human settlement changing ecosystem patterns and processes across most of the terrestrial biosphere (Ellis & Ramankutty, 2008; Ellis et al., 2013; Martin et al., 2012). Human presence is so pervasive on earth that some argue it marks a new geological epoch, the Anthropocene (Steffen et al., 2011).[2] The world today is a blend of anthropogenic and non-anthropogenic factors and *prima facie* this seems like a world in which exchange between ecology and economics would be a prerequisite to successful science.

Recent discussions in the philosophy of science about idealization can help illuminate this state of affairs (Weisberg, 2007).[3] Invariably, theorizing involves intentional distortions and simplifications, and theoreticians must make decisions about which factors to include in their models and which to ignore. These decisions can be made for pragmatic reasons, for example, to simplify a model so that it is computationally or cognitively tractable (referred to as *Galilean Idealizations*). They are also made because ignoring some factors is believed to be causally innocuous (*Minimalist Idealization*). The relevant concerns for any idealization are (i) whether the factor that was omitted from, or distorted in, the model would substantially change the predictions or explanatory power of the model if it had been taken into account, and (ii) if the predictions or explanatory power are substantially changed, what we should do about the idealization. Practitioners making Galilean idealizations would justify the omission of such factors on grounds of tractability; those making minimalist idealizations could not justify such omissions.

We argue that there are cases in which ignoring economic factors leads to poor predictions in ecology and cases when ignoring ecological factors leads to poor policy prescriptions in economics. For all such cases, if we presume that *the goal is to obtain successful predictions and, ultimately, recommend successful policy interventions*, then *Minimalist* idealization is straightforwardly unwarranted, given that excluding such causal factors is not innocuous. Although *Galilean* idealization is not unwarranted, since simple models that exclude one set of factors may indeed be more tractable, this type of idealization does not fit well with the goal of recommending successful policy interventions which, as we show below, depends on predictive success as well as tractability. In other words, if the best predictions and prescriptions for policy intervention require hybrid economic-ecological models containing anthropogenic and non-anthropogenic causal factors, then such factors should not be omitted merely on grounds of idealization.

The main argument of this article can be summarized as follows. There is a growing consensus that the world now consists of systems containing interdependent anthropogenic and non-anthropogenic factors, but ecology has tended to idealize anthropogenic factors and economics has tended to idealize non-anthropogenic factors. Although idealizations in general can be justified pragmatically or because they are innocuous, our claim is that not every idealization in ecology and economics can be so justified. We question whether the idealizations in ecology and economics are justified pragmatically given, first, that integration between these disciplines, as defined further below, need not be disruptive to traditional disciplinary practices, and thus *not* a computational or cognitive burden, and, second, that our best chance of providing successful predictions, and also successful policy interventions, is integration. We conclude that the recent evidence, which suggests that many of the world's systems contain interdependent anthropogenic and non-anthropogenic factors, is a new and independent reason for promoting and fostering interdisciplinary integration.

3. Interdisciplinarity and the Philosophy of Science

Philosophers of science have a growing interest in interdisciplinary science (Gibbons et al., 1994; Longino, 2013; MacLeod & Nagatsu, 2016; MacLeod & Nagatsu, 2018; see also the references above and below). Many acknowledge that collaborations between researchers working in different disciplines is a requirement for addressing the complex environmental, societal, and medical problems that we currently face – often under the rubrics of 'real-world problems,' 'wicked problems,' or 'grand challenges' – and so frameworks that help us to understand when and why such collaborations will be productive and unproductive are essential. This literature has focused on a number of questions, including: What social, institutional, organizational, and cognitive factors hinder interdisciplinary exchange and integration (MacLeod, 2018; O'Malley, 2013)? What factors promote exchange (Crow & Dabars, 2015)? How do different disciplines coordinate and modify their existing conceptual and linguistic frameworks (Bracken & Oughton, 2006)? How do they come to terms with different epistemic and explanatory standards (Calvert & Fujimura, 2011)?

This article contributes to this literature in a novel way by focusing on specific cases where interdisciplinary science seems imperative. We argue that recognizing human-natural-coupled systems as the new normal should encourage exchanges between ecology and economics, exchanges that have traditionally been discouraged by disciplinary boundaries. The interdisciplinary literature, in both philosophy of science and science itself, has developed a complex terminology to characterize the complexity of interdisciplinary work itself. And so before turning to our central claims, we have to start with this terminology.

In the interdisciplinarity literature, interdisciplinary exchange, transfer, collaboration, and integration have separate, and often ambiguous, meanings. Following Grüne-Yanoff et al. (2014), an *exchange* is a process or event that occurs when objects (like models, theories, or data) or tools (like inference, modeling, or experimental methods) employed in one discipline are used to solve problems of another discipline. Exchange is thus a general term for interdisciplinary work of many different kinds. Following Brigandt (2013), we recognize that the 'kinds of units' of exchange can be various. A *transfer* occurs when agents from *only* one discipline pursue an exchange, that is, cases in which 'an object from one discipline is employed to address a problem from another discipline' (Grüne-Yanoff et al., 2014, 55). A *collaboration*, in contrast, involves agents from different disciplines who work together, for example, to create a new model or who jointly pursue an exchange. Both of our case studies provided below are examples of interdisciplinary transfer, rather than collaboration.

Unlike exchange, transfer, and collaboration, *integration* is a more complicated term in the literature. As demonstrated by Holbrook (2013) and O'Rourke et al. (2016), although integration is recognized as a 'central feature of cross-disciplinarity' (O'Rourke et al., 2016, p. 63) there is little agreement on just what integration amounts to. It is also widely recognized that the kinds of units of integration can be various: fields, approaches, specialties, disciplines, data, models, methods, and explanations have all, for example, been the subject of philosophical studies of integration (Brigandt, 2013, p. 463). The traditional or received view is that disciplinary integration involves a significant or complete breakdown of disciplinary boundaries in the pursuit of interdisciplinary science. As Brigandt (2013) notes, this treats integration as akin in meaning and use to more traditional concepts of synthesis and unification. Grüne-Yanoff (2016, p. 347) characterizes this position when he writes, 'According to [a commonly held position], interdisciplinary research is successful if it integrates disciplines, creates new academic programs and ultimately new disciplines. This position is often understood in the strong sense that integration is not only a contributing factor to interdisciplinary success, but also a necessary condition for it.' On this understanding, then, integration is a specific form of exchange involving significant disciplinary breakdown or the creation of a new field – and, on this view, such breakdown or synthesis is central to the success of interdisciplinarity itself. Both MacLeod and Nagatsu (2018) and Grüne-Yanoff (2016) have recently argued that understanding interdisciplinarity as requiring this form of integration commits interdisciplinary research to an unrealistic and unjustifiably burdensome level of commitment and collaboration, and we agree. Taking a close look at actual interdisciplinary practices in the environmental sciences, MacLeod and Nagatsu (2018) suggest that such practices 'crystallize' around four types of methodological strategies – discussed further below – none of which require this strong form of integration as significant disciplinary boundary breakdown.

One option would be to see integration as one kind of *product* of interdisciplinary exchange: when exchange results in significant disciplinary breakdown. The issue is, as MacLeod and Nagatsu (2018) point out, interdisciplinarity is often defined in terms of integration. For example, the National Academy of Sciences (2006) defines it as …

> "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of

> specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice." (MacLeod & Nagatsu, 2018, p. 75)

Our terminological solution, in concert with MacLeod and Nagatsu (2018) and Grüne-Yanoff (2016), is to treat integration as synonymous with exchange, as defined above, as a general term that refers to interdisciplinary processes and events. This also fits with the recent proposal by O'Rourke et al. (2016) that integration be understood as a 'parameterizable input-output process that yields different types of integration in different contexts' (2016, p. 69). Below we sometimes use the word 'exchange,' since it has less baggage than integration, but we use these terms synonymously.

The case studies we provide below – also in concert with recent arguments by Grüne-Yanoff (2016) and MacLeod and Nagatsu (2018) – demonstrate that significant epistemological advantages can be purchased, in some cases, relatively cheaply, without requiring significant and disruptive disiplinary integration and with minimal collaboration. In other words, significant and disruptive disciplinary integration may be beneficial in some cases, but it is certainly not *required* to address problems that require multiple disciplinary specialties for solutions.

The following case studies also speak to some of the more traditional questions about interdisciplinarity. Consider, for example, the specific epistemic virtues generated by interdisciplinary exchange between ecologists and economists. Miles MacLeod and Nagatsu (2016) follow a similar line of reasoning when they argue that successful interdisciplinary collaboration provides practitioners with 'collaborative gains,' such as better predictive power or explanatory scope. Because our case studies of interdisciplinary exchange involve little bidirectional collaboration compared to that of MacLeod and Nagatsu (2016), we will call these epistemological and policy-oriented advantages 'exchange gain.' Moreover, our analysis provides further evidence to support the claim that successful interdisciplinary interaction does not always require the breakdown of disciplines (Grüne-Yanoff, 2016). In the case of interdisciplinary exchange between ecology and economics, considerable epistemic gains, along with improved policy prescriptions, can be obtained without a thoroughgoing integration of ecology and economics. We call these types, following the typology given by Grüne-Yanoff et al. (2014), of interdisciplinary exchange *non-disruptive model-variable transfer* and *non-disruptive model-system transfer*. Below, we also describe how these types fit into MacLeod and Nagatsu's (2018) interdisciplinary 'modeling strategies.' While we do not deny that there may be some cases that would require the complete integration of ecology and economics, or the synthesis of a new field, our claim is that such an assimilation is not a necessary condition for attaining various epistemological benefits that arise from interdisciplinary exchange between ecology and economics. Our analysis shows that the disciplinary identities of these two sciences can remain, on the whole, intact.

4. When Ecology Needs Economics: Island Biogeography in the Anthropocene

Traditionally, ecologists have ignored anthropogenic factors, often discounting human activity as external to ecosystems and treating humans as exogenous variables or disturbing conditions (for examples, see: DesRoches et al., 2019; Inkpen, 2017a; Martin et al., 2012; O'Neill & Kahn, 2000; Sagoff, 2017; Worm & Paine, 2016). Ecologist James Brown wrote in 1995 that the 'study of humans and their interrelationships with the rest of the natural world has been left to the "social" and the "applied" sciences, both of which have been viewed with disdain by many of those who practice "pure" ecology' (Brown, 1995, p. 205).[4]

As Collins et al. (2000) famously suggested, one reason for this treatment of anthropogenic factors is the assumption that human-disturbed environments are unpredictable from an ecological standpoint. Human actions are often governed by individual whim or social forces – whether cultural, political, or economical – that are on a different disciplinary level from what are thought of as ecological variables, like foraging or dispersal strategies (Inkpen, 2017a). Without including anthropogenic factors, the dynamics of 'human-disturbed' systems appear unpredictable. To predict the changing composition of species making up a human-planted forest or city park an ecologist must include variables, which capture the intentions of forest managers or urban designers.[5]

Acknowledging the now pervasive influence of humans on the planet, many recent ecologists have begun to include human activity in their models (Ellis, 2015; Pelletier & Coltman, 2018). They want an ecology that applies to human-disturbed as well as undisturbed landscapes, but this forces them to take into account economic processes, among other human processes. One field where this interdisciplinary exchange is occurring is biogeography (Mendenhall et al., 2013; Thomas, 2013). The theory of island biogeography is particularly important because it has long been the foundation for estimating extinction rates, predicting changes in biodiversity, and making policy recommendations (Diamond, 1975; He & Hubbell, 2011). We present one recent example from this literature (Helmus et al., 2014).

The theory of island biogeography explains and predicts the species richness (that is, number of species) that will be found on an island at equilibrium (that is, when rates of species immigration to the island and species extinction on the island balance out) (Diamond, 1975; MacArthur & Wilson, 1967). In a recent article, Helmus et al. (2014) tested the predictions of this theory for the distribution of *Anolis* lizard species among Caribbean islands. The theory predicts a strong negative relationship will be found between species richness and geographic isolation: as a result of decreased inter-island immigration, more isolated islands will contain fewer species than less isolated ones. It turns out that this prediction is false for Caribbean *Anolis* lizards because geographic isolation no longer determines immigration of new species. Rather, it is *economic* isolation that does so: islands that receive more cargo shipments are more likely to contain migrants from other islands, as lizards can move from island to island as stowaways on human cargo ships. For Caribbean lizards, that is, geographic isolation is of less influence on biodiversity than economic isolation. Estimating economic isolation from global maritime shipping-traffic data, Helmus et al. found that when economic isolation was substituted for geographic isolation, the new biogeographic theory fit with their data: anole richness was a negative function of economic isolation. They conclude that 'Unlike the island biogeography of the past that was determined by geographic area and isolation, in the Anthropocene [...] island biogeography is dominated by the economic isolation of human populations. [And] Just as for models of other Earth systems, biogeographic models must now include anthropogenic [variables] to understand, predict, and mitigate the consequences of the new island biogeography of the Anthropocene' (Helmus et al., 2014, p. 543, 546). This is a clear case of unidirectional interdisciplinary exchange and the *exchange gain* in this case is predictive accuracy.

But the case is even stronger. Building anthropogenic factors into their biogeographic model also gives Helmus et al. a way to predict – with the aim of mitigating – the effects of decreasing economic isolation. For example, as economic isolation decreases, we must increase our efforts to protect exotic species from the immigration of non-native species, if that is the conservation strategy adopted. Traditional theories of biogeography that do not include anthropogenic factors may provide few resources – or worse, may actually suggest inapplicable, harmful strategies – for the conservation of these Caribbean lizards because the variables that make a difference are not included in the model. To know whether economic isolation is going to increase or decrease one must follow economic trends. For example, the US embargo increases Cuban economic isolation, and a cessation of the embargo would decrease isolation and increase species richness. Helmus et al. predict that Cuba would rapidly gain between 1 and 2 non-native anole species, a prediction that could not be made with the traditional (non-anthropogenic) biogeographic theory.

What can we learn from this example? Not that ecologists should always take anthropogenic factors into account in *every* case. Rather, that (i) there are cases in which not taking anthropogenic factors into account can be epistemically disadvantageous, such as diminishing our ability to predict the dynamics of certain systems, and (ii) that such cases are not limited to urban or agricultural settings, but range over cases of 'pure' ecology such as the distributions of *Anolis* lizards on Caribbean islands (see also: Pelletier & Coltman, 2018).

Helmus et al.'s article demonstrates that if the goal is the successful prediction of ecological systems, with the hope of providing helpful advice for policy interventions, there are compelling reasons for encouraging interdisciplinary exchange between ecology and economics. This is a clear case of when ecology needs economics: not taking anthropogenic activities into consideration in the construction of a biological model diminishes our ability to predict the dynamics of systems to which that model *is* intended to apply.[6]

Furthermore, connecting this discussion to that in Section 2, it is likely that as coupled human-natural systems, like anole distribution in the Caribbean, become the new norm, coupled economic-ecological models will be required. A science of ecology that leaves out anthropogenic factors will likely lose global relevance as the places in which its theories apply diminish. In other words, such an omission, whether based on a Galilean or minimal idealization, would seem to be unjustified. Rather than look at this with disappointment or scorn, a better response is to aim for models which *can* accommodate such systems, and this means championing interdisciplinary exchange (although it should be said that this conclusion does not imply that the only way to achieve success is to create a new interdiscipline – in some cases, such as this case, what is needed is interdisciplinary exchange, rather than synthesis or unification).

Exchange gain is purchased at little cost in this case. It doesn't require the development of a new theoretical framework nor extensive disciplinary integration, and requires minimal bidirectional collaboration. Instead, what was needed was the substitution of a variable strongly influenced by economic trends – economic isolation – with one that is common in traditional ecology – geographical isolation. Here, traditional ecological theory is retained in a modified form. We call this type of interdisciplinary exchange *non-disruptive model-variable transfer*: an economic variable is simply substituted for an ecological one in a traditional ecological model.

How does the interdisciplinary exchange exemplified by the Helmus et al. study compare to typical interdisciplinary modeling strategies? MacLeod and Nagatsu (2018) have recently argued that the majority of modeling strategies among interdisciplinary scientists typically fall into one of four main categories: data-driven modeling, modular model coupling, integral modeling, and substitutive modeling. Data-driven modeling strategies typically employ a statistical modeling platform such as multiple regression analysis, and scientists from different disciplines contribute their own data sets. Integral modeling, on the other hand, employs a particular domain-neutral modeling framework to combine information from different disciplines. Agent-based modeling is a prime example of integral modeling among environmental scientists. Modular model-coupling denotes integrated assessment models, such as those used by economists to anthropogenic model climate change. Such models are characterized by certain output variables from a component model serving as an input into another component model. Finally, substitutive modeling is perhaps the rarest interdisciplinary modeling strategy, according to MacLeod and Nagatsu (2018). They state, substitutive model-coupling occurs 'when two fields share model templates of roughly similar structure for solving given classes of problems, but use simplified methods and representations for components of those templates, which another field can handle with much more sophistication' (2018, p. 80).

None of the foregoing modeling strategies – data-driven modeling, modular model coupling, integral modeling, or substitutive modeling – captures the minimalist interdisciplinary exchange demonstrated by the Helmus et al. study. Arguably, non-disruptive model-variable transfer is a rare kind of interdisciplinary exchange that requires less integration than any of the four main modeling strategies identified by MacLeod and Nagatsu (2018). Studying island biogeography during the Anthropocene appears to present a special case in terms of typical interdisciplinary modeling strategies adopted by environmental scientists.

5. When Economics Needs Ecology: Cutthroat Trout in Yellowstone Park

Economists have generally discounted the significance of ecological factors in their models and theories. They have often presumed that non-human factors are either fixed, exogenous, or disturbing causes. Even the most esteemed nineteenth century economic theorists who endorsed the Malthusian population principle downplayed the role of such factors in their models. David Ricardo, for instance, inaugurated this trend with his 'corn model', where land is depicted as an original and 'indestructible factor of production' ([1817] 1951, p. 67).[7] Subsequent Ricardians, such as Mill, [1848] 2006, not only sanctioned this view of land but drove a wedge between the social and natural realms by repositioning the entire core of phenomena studied by economists such that human agency is the proximate cause (Schabas, 2005).

Today, many economists have begun to wrestle with their Ricardian inheritance. The Cambridge economist, Partha Dasgupta, for example, contends that resource economists can no longer afford to assume that 'Nature' is an 'indestructible factor of production' (2010, p. 6). Others have abandoned their Ricardian legacy altogether. In fact, the entire interdisciplinary field of research ecological economics emphasizes the significance of including social and ecological factors in coupled or ecological-economic models (Christensen, 1989; Costanza, 1989; Martinez-Alier & Røpke, 2008; Røpke, 2005; Van den Bergh, 2001). Be that as it may, ecological-economic modeling is not yet a widespread practice among mainstream resource economists (Wätzold et al., 2006).

According to Dasgupta, the central reason why resource economists should no longer assume that ecological factors are fixed is because this assumption can have harmful consequences if the goal is to make optimal policy prescriptions (Dasgupta et al. 2002). Simon Levin et al. (2013) and Kenneth Arrow et al. (1995) concur. Levin et al. (2013) give the example of modeling coral reefs with conventional economic instruments, such as taxation, trading schemes, and quotas, and argue that without modeling such phenomena as complex adaptive systems (systems linking anthropogenic and non-anthropogenic factors), policy interventions are much less effective than they would be otherwise. Since the management of coral reefs is characterized by nonlinear feedbacks, strategic interactions, individual and spatial heterogeneity, and varying time scales, ignoring such complex characteristics lead to failures in predicting profound changes to economically important ecosystems. For instance, a coral reef may 'flip' from having a healthy population of tropical fish to being an algae-dominated one and, by using a model that excludes the variables that determine such abrupt regime shifts, economists are incapable of predicting large negative economic consequences (in this case, for fisheries and tourism) associated with this kind of shift. Arrow et al. (1995) gives the example of including dynamic ecological factors in economic growth models. They argue that ecological factors, such as the carrying capacity of the environment, should be included in growth models to ensure that 'the ecological systems on which our economies depend are resilient' (1995, p. 521). Their central worry is that modeling growth without accounting for the resilience of ecosystems could make societies unnecessarily sensitive to harmful external shocks. Growth models should be structured so that they never prescribe policies that undermine the ecological conditions that make human economic activity possible in the first place.

Nowhere are the epistemological and policy benefits of including ecological factors in economic models more evident than in the case of managing invasive species in Yellowstone National Park, Wyoming. When Yellowstone Lake was invaded by an exotic lake trout (*Salvelinus namaycush*), managers were worried that the growth of this species would significantly reduce the population level of the Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), a native species that supports an inland fishery and a variety of non-human species, such as ospreys, pelicans, river otters, and grizzly bears. Chad Settle et al. (2002) specified a model for two separate systems: the economic system in Yellowstone National Park and the ecosystem in and around Yellowstone Lake. They asked whether their model, which combines details of an economic system and an ecosystem with explicit feedback links (economic and ecological factors are jointly determined) between them, yields significantly different results than a model that ignores those links. Their economic-ecological model, predicted that when ecosystems change, people will change their economic behavior, which in turn affects the ecosystem; correspondingly, any alterations in the ecosystem affects human economic behavior, including economic production possibilities.

Settle et al. (2002) ran three different scenarios with their model. The best-case scenario is a hypothetical one, when the lake trout are costlessly eliminated from Yellowstone Lake. Under this optimistic scenario, the cutthroat trout would return to the lake as if the lake trout had never invaded in the first place. The worse-case scenario occurs if the lake trout are left to their own devices, which would have the effect of producing the smallest viable population of cutthroat trout. Their third policy scenario involved the National Park Service gillnetting the lake trout in order to reduce the risk to cutthroat trout populations.

Their results showed that a dynamic model that integrates ecological and economic systems with feedback links between the two systems not only yields significantly different results than when one that ignores these links, but that model which allows feedback is capable of making better predictions and, therefore, better policy prescriptions. In fact, for every scenario that Settle et al. (2002) outline, cutthroat trout populations differ in both magnitude and survival rates *once feedback is allowed* between the two systems. For the best-case and policy scenarios, these authors predict the steady state population of cutthroat would be lower without feedback than with feedback. Ignoring feedback between the two systems would result in overestimating the cutthroat population, with potentially negative consequences for policy prescriptions. Settle et al. conclude that 'basing policy recommendations in Yellowstone Lake on data from models without feedback puts cutthroats at greater risk than would be true if feedback was explicitly considered' (2002, p. 309). In this case, the policy recommendations derived from a model without ecological factors would be worse than those derived from a model that connects the economic system to an ecological system with explicit feedback links. Without allowing for such dynamics, managers risk inferring that the steady state population of cutthroat is higher than it actually is. In this case, an economic model without feedback links to the ecosystem would make substandard predictions and policy prescriptions.

As with the Helmus et al. case in the previous section, the exchange gain in the cutthroat trout example can be purchased rather cheaply. The latter does not require the development of a completely new theory or bidirectional collaboration. Instead, Settle et al.'s model merely required the addition of feedback variables that link two jointly determined systems. In this case, the economic variables that constitute the economic system, are not jettisoned or even supplanted by another variable. Rather, the traditional economic theory is retained, but in a supplementary form. We can call this type of interdisciplinary exchange *non-disruptive model-system transfer*: an ecological system with feedback links is connected to a traditional economic system. This exchange contrasts sharply with types of disruptive model transfer involving the development of entirely new theory.

How might we categorize this instance of *non-disruptive model-system transfer* in light of the interdisciplinary modeling strategies identified by MacLeod and Nagatsu (2018), as discussed in the previous section? The *non-disruptive model-system transfer* employed by Settle et al. is best captured by what MacLeod and Nagatsu (2018) describe as 'modular model-coupling.' Recall, that this particular modeling strategy involves output variables from component models serving as input to other component models. This is precisely what we have in the case of Settle et al.'s study, which blends the details of an economic system and an ecosystem with feedback links (jointly determined) between them. This strategy appears to have enabled Settle et al. to connect preexisting economic and ecological models rather than, for example, comprehensively integrate various methods and concepts from both economics and ecology.

6. Conclusion

Recent scientific evidence forces scientists to acknowledge the prevalence of systems containing factors that transgress disciplinary boundaries. This state of affairs has consequences for both ecology and economics. The practitioners of these two sciences have traditionally found themselves occupied with phenomena on opposite sides of the human-natural divide. Yet, in many cases, human-natural-coupled systems are the new norm. We have argued that there are specific cases in which these sciences fare better, epistemologically, and in terms of policy prescriptions, when they work together to build models that contain anthropogenic and non-anthropogenic factors, compared to when they address these factors separately. In the first case, ecologists demonstrated that supplanting an ecological variable with an economic one gave rise to a model, which had a better fit with current data and offered better prospects for predicting future changes in biodiversity. In the second case, economists maintain an economic system from their model, but connect it to a distinct system, an ecological system, with feedback variables that link the two systems together. Of course, our claim is not that ecology always needs economics, and economics always needs ecology. Modeling organism behavior in the trenches of the deep ocean, for example, may not require economics and predicting the unemployment rate will almost certainly not benefit from ecology.

Our analysis contributes to the recent literature about interdisciplinarity in at least three ways. First, we argued that recent scientific evidence demonstrating that human-natural-coupled systems are the new norm should itself encourage interdisciplinary exchange, and we spelled this out in terms of exchange gain in two different case studies. Second, we showed that exchange between disciplines can bring about epistemological advantages without requiring disciplinary breakdown. This conclusion is striking because many philosophers of science have supposed that breakdown is essential to interdisciplinary science, as discussed in Section 3 above (Brigandt, 2013). By contrast, our article adds additional support for the relatively new claim that successful interdisciplinary interaction does not always require breakdown (Grüne-Yanoff, 2016; MacLeod & Nagatsu, 2018).

Third, following the types of possible interdisciplinary exchange summarized by Grüne-Yanoff et al. (2014), we have characterized these types of exchanges as non-disruptive model-variable transfer and non-disruptive model-system transfer. Recently, MacLeod and Nagatsu (2018) have argued that interdisciplinary practices have crystallized around four preexisting methodological frameworks, as described above. Since in practice, at least in the environmental sciences, interdisciplinary research seems to invoke this limited set of 'conservative model-building frameworks' (2018, p. 81), they argue that an important way forward is to work on standardizing these types of currently helpful frameworks. Our case of the Cutthroat trout supports their analysis in a straightforward way: it is an example of modular model-coupling. And this is further evidence that this modeling framework is common and should be standardized. Our example of island biogeography, however, does not clearly fit into any of these four modeling strategies. Given that their analysis is not exhaustive of interdisciplinary practices, this is consistent with their analysis, but perhaps shows that room should be left for even simpler forms of interdisciplinarity science. Sometimes all that is needed is model-variable transfer, as per Grüne-Yanoff et al. (2014).

Our analysis also has a wider implication. In the case of ecology and economics, as with many sciences, disciplinary ideals, and commitments can discourage cross-disciplinary interaction. We agree with ecologist James Brown, in the quotation given above, that interactions between ecologists and economists have been structured by ideas of 'pure' versus 'applied' science: 'pure' ecologists study non-human nature and 'pure' economists often overlook non-human nature (Brown, 1995).[8] Yet, during the Anthropocene, we have strong scientific evidence to believe that most of the terrestrial globe consists of coupled human-natural systems, and we have just provided evidence that such systems are better considered as wholes, rather than the separate objects of two independent sciences. Our aim has not been to argue that we should revolutionize the divisions of science, however, but to urge that they do not always reflect evidence about our current world, and thus that the divisions themselves should not structure or determine interactions across disciplines. We agree with ecologists Boris Worm and Robert Paine that 'the recognition of a novel geological epoch might also provide a new focus for ecology and the study of humans as a primary and dominant component of contemporary ecosystems,' but we would add that this will require interaction with social scientists, including economists (Worm & Paine, 2016, p. 601). And, the reverse is true as well: it seems likely that, in a growing number of cases, economics will need ecology, too. Indeed, in the age of the Anthropocene, without interdisciplinary exchange it is to be expected that ecology and economics would relinquish global relevance because the distinct and separate systems to which each pure science applies will only diminish over time.

Notes

1. Ecological Economics is a policy-oriented school of thought that emerged as a formal institution in the late 1980s, with its origins extending back to Nicholas Georgescu-Roegen's *The Entropy Law and Economic Processes* (1971).
2. The term 'Anthropocene' was coined by Nobel laureate Paul Crutzen in year 2000 to describe the current geological epoch that is characterized by the enormous role that human activity has for geological and ecological phenomena (Jones, 2011).
3. For earlier contributions to this literature, see Cartwright (1989) and Mäki (1992). Following Jones (2005) it has been common to draw a distinction between *idealization* and *abstraction*, the former being the assertion of a falsehood, the latter being merely an omission. In this article, we follow Weisberg's (2007) pluralist account and treat abstraction as a form of minimalist idealization, as I explain below.
4. According to Laura Martin and colleagues, 'most ecologists have assumed that (seemingly) unpeopled environments better represent ecological and evolutionary processes and are therefore better objects of study' (Martin et al., 2012, p. 198). And James Collins and colleagues write that 'From the perspective of a field ecologist examining a natural ecosystem, people are an exogenous, perturbing force' (Collins et al., 2000, p. 416; see also Alberti et al., 2003, p. 1173; MatthewChew, 2009, p. 148).

5. See Johnson and Swan (2014) for a discussion of human landscaping preferences that might help build predictive urban ecology models.
6. Of course, that is not to say that economics is the only discipline that gives us information about anthropogenic activities
7. See Morgan (2012, p. 44-81).
8. To be clear, our claim is not that any ecologists and economists consciously decide to exclude certain causal factors on the basis of purity. Instead, our claim is historical. Ecology and economics happen to be scientific disciplines that formed around explaining some causal relations, while precluding others.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

C. Tyler DesRoches http://orcid.org/0000-0002-7318-6948

References

Alberti, M., Marzluff, J., Shulenberger, E., Bradley, G., Ryan, C., & Zumbrunnen, C. (2003). Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. *BioScience*, *53*(12), 1169–1179. https://doi.org/10.1641/0006-3568(2003)053[1169:IHIEOA]2.0.CO;2

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B.-O., Levin, S., Maler, K.-G., Perrings, C., & Pimentel, D. (1995). Economic growth, carrying capacity, and the environment. *Science.*, *268*(5210), 520–521. https://doi.org/10.1126/science.268.5210.520

Bensaude-Vincent, B., & Newman, W. R. (2007). *The artificial and the natural: An evolving polarity*. MIT Press.

Bonneuil, C., & Fressoz, J. (2015). *The shock of the anthropocene: The earth, history and us*. Verso.

Bostic, H. (2016). The humanities must engage global grand challenges. *Chronicle of Higher Education*, *30*(March), 2016. https://www.chronicle.com/article/the-humanities-must-engage-global-grand-challenges/

Bostic, H., & Howey, M. (2017). The anthropocene needs the liberal arts. *Anthropocene*, *18*, 105–110. https://doi.org/10.1016/j.ancene.2017.06.002

Bracken, L. J., & Oughton, E. A. (2006). What do you mean? The importance of language in developing interdisciplinary research. *Transactions of the Institute of British Geographers*, *31*(3), pp.371–382. https://doi.org/10.1111/j.1475-5661.2006.00218.x

Brigandt, I. (2013). Integration in biology. Philosophical perspectives on the dynamics of interdisciplinarity. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *44*(4), 461–465. https://doi.org/10.1016/j.shpsc.2013.09.009

Brown, J. (1995). *Macroecology*. Chicago University Press.

Calvert, J., & Fujimura, J. H. (2011). Calculating life? Duelling discourses in interdisciplinary systems biology. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *42*(2), pp.155–163. https://doi.org/10.1016/j.shpsc.2010.11.022

Cartwright, N. (1989). *Nature's Capacities and Their Measurement*. Oxford University Press.

Castree, N. (2014). The Anthropocene and the environmental humanities: Extending the conversation. *Environmental Humanities*, *5*(1), 233–260. https://doi.org/10.1215/22011919-3615496

Chakrabarty, D. (2009). The climate of history: Four theses. *Critical Inquiry*, *35*(2), 197–222. https://doi.org/10.1086/596640

Chew, M. (2009). Good ideas at the time: Historians look at ecology. *Bulletin of the Ecological Society of America*, *90*(1), 142–152. https://doi.org/10.1890/0012-9623-90.1.142

Christensen, P. P. (1989). Historical Roots for Ecological Economics – Biophysical versus allocative approaches. *Ecological Economics*, *1*(1), 17–36. https://doi.org/10.1016/0921-8009(89)90022-0

Collins, J., Kinzig, A., Grimm, N., Fagan, W., Hope, D., Wu, J., & Borer, E. (2000). A new urban ecology: Modelling human communities as integral parts of ecosystems poses special problems for the development and testing of ecological theory. *American Scientist*, *88*(5), 416–425.

Corlett, R. (2015). The Anthropocene concept in ecology and conservation. *Trends in Ecology & Evolution*, *30*(1), 36–41. https://doi.org/10.1016/j.tree.2014.10.007

Costanza, R. (1989). What is ecological economics? *Ecological Economics*, *1*(1), 1–7. https://doi.org/10.1016/0921-8009(89)90020-7

Crow, M. M., & Dabars, W. B. (2015). *Designing the New American University*. JHU Press.

Darden, L., & Maull, N. (1977). Interfield Theories. *Philosophy of Science*, *44*(1), 43–64. https://doi.org/10.1086/288723

Dasgupta, P. (2010). Nature's Role in sustaining economic development. *Philosophical Transactions of the Royal Society: Biological Sciences*, *365*(1537), 5–11. https://doi.org/10.1098/rstb.2009.0231

Dasgupta, P., Levin, S., & Subchenco, J. (2002). Economic Pathways to Sustainability. *Bioscience*, *50*(4), 339–345. https://doi.org/10.1641/0006-3568(2000)050[0339:EPTES]2.3.CO;2

De Grandis, G., & Efstathiou, S. (2016). Introduction—grand challenges and small steps. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *56*, 39–47. https://doi.org/10.1016/j.shpsc.2015.11.009

DesRoches, C. T., Inkpen, S. A., & Green, T. L. (2019). The eroding artificial/natural distinction? Some consequences for ecology and economics. In M. Nagatsu & A. Ruzzene (Eds.). *Contemporary Philosophy and Social Science: An Interdisciplinary Dialogue* (pp. 39–57). London, UK: Bloomsbury Publishing.

Diamond, J. (1975). The Island dilemma: Lessons of modern biogeographic studies for the design of nature reserves. *Biological Conservation*, *7*(2), 129–146. https://doi.org/10.1016/0006-3207(75)90052-X

Ellis, E. (2015). Ecology in an Anthropogenic Biosphere. *Ecological Monographs*, *85*(3), 287–331. https://doi.org/10.1890/14-2274.1

Ellis, E., Maslin, M., Boivin, N., & Bauer, A. (2016). Involve social scientists in defining the Anthropocene. *Nature News*, *540*(7632), 192. https://doi.org/10.1038/540192a

Ellis, E., & Ramankutty, N. (2008). Putting people in the map: Anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, *6*(8), 439–447. https://doi.org/10.1890/070062

Ellis, E., Kaplan, J., Fuller, D., Vavrus, S., Goldewijk, K., & Verburg, P. (2013). Used planet: A global history. *Proceedings of the National Academy of Science*, *110*(20), 7978–7985. https://doi.org/10.1073/pnas.1217241110

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., & Trow, M. (1994). *The new production of knowledge: The dynamics of science and research in contemporary societies*. Sage.

Grüne-Yanoff, T. (2016). Interdisciplinary success without integration. *European Journal for Philosophy of Science*, *6*(3), pp.343–360. https://doi.org/10.1007/s13194-016-0139-z

Grüne-Yanoff, T., & Mäki, U., (2014). Introduction: Interdisciplinary model exchanges. *Studies in History and Philosophy of Science Part A*, *48*, 52–59. https://doi.org/10.1016/j.shpsa.2014.08.001

Grüne-Yanoff, T., & Morgan, M. (2013). Modeling practices in the social and human sciences. An interdisciplinary exchange. *Perspectives on Science*, *21*(2), 143–156. https://doi.org/10.1162/POSC_a_00089

He, F., & Hubbell, S. (2011). Species-area relationships always overestimate extinction rates from habitat loss. *Nature*, *473*(7347), 368–371. https://doi.org/10.1038/nature09985

Helmus, M. D., Mahler, L., & Losos, J. (2014). Island biogeography of the Anthropocene. *Nature*, *513*(7519), 543–546. https://doi.org/10.1038/nature13739

Holbrook, J. B. (2013). What is interdisciplinary communication? Reflections on the very idea of disciplinary integration. *Synthese*, *190*(11), pp.1865–1879. https://doi.org/10.1007/s11229-012-0179-7

Huutoniemi, K., Klein, J. T., Bruun, H., & Hukkinen, J. (2010). Analyzing interdisciplinarity: Typology and indicators. *Research Policy*, *39*(1), pp.79–88. https://doi.org/10.1016/j.respol.2009.09.011

Inkpen, S. A. (2017a). Are humans disturbing conditions in ecology? *Biology & Philosophy*, *32*(1), pp.51–71. https://doi.org/10.1007/s10539-016-9537-z

Inkpen, S. A. (2017b). Demarcating nature, defining ecology: creating a rationale for the study of nature's primitive conditions. *Perspectives on Science*, *25*(3), pp.355–392. https://doi.org/10.1162/POSC_a_00246

Inkpen, S. A., & DesRoches, C. T. (2019). Revamping the Image of Science for the Anthropocene. *Philosophy, Theory and Practice in Biology*, *11*(3), 1–7. http://dx.doi.org/10.3998/ptpbio.16039257.0011.003

Johnson, A., & Swan, C. (2014). *Drivers of Vegetation Species Diversity and Composition in Urban Ecosystems*. Springer.

Jones, M. (2005). Idealization and abstraction: A framework. In M. Jones & N. Cartwright (Eds.). *Idealization XII: Correcting the Model*. (pp. 173–217). Rodopi, New York.

Jones, N. 2011. *Human influence comes of age*. Nature, (473), 133. http://www.nature.com/news/2011/110511/full/473133a.html.

Kitcher, P. (1999). Unification as a Regulative Ideal. *Perspectives on Science*, *7*(3), pp.337–348. https://doi.org/10.1162/posc.1999.7.3.337

Laurance, W. (2010). *Beyond Island biogeography theory: Understanding habitat fragmentation in the real world*. inJ. Princeton University Press.

Ledford, H. (2015). Team Science. *Nature*, *525*(7569), 308–311. https://doi.org/10.1038/525308a

Levin, S., Xepapadeas, T., Norberg, C. J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., Ehrlich, P., Kautsky, N., Mäler, K.-G., Polasky, S., Troell, M., Vincent, J. R., & Walker, B. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics*, *18*(2), 111–132. https://doi.org/10.1017/S1355770X12000460

Liu, J., Dietz, T., Carpenter, S., Alberti, M., Folke, C., Moran, E., Pell, A., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C., Schneider, S., & Taylor, W. (2007a). Complexity of coupled human and natural systems. *Science*, *317*(5844), 1513–1516. https://doi.org/10.1126/science.1144004

Liu, J., Dietz, T., Carpenter, S., Folke, C., Alberti, M., Redman, C., Schneider, S., Ostrom, E., Pell, A., Lubchenco, J., Taylor, W., Ouyang, Z., Deadman, P., Kratz, T., & Provencher, W. (2007b). "Coupled Human and Natural Systems.". *Ambio*, *36*, 639–649. https://doi.org/10.1579/0044-7447(2007)36[639:CHANS]2.0.CO;2

Longino, H. E. (2013). *Studying human behavior: How scientists investigate aggression and sexuality*. University of Chicago Press.

Love, A., & Lugar, L. (2013). Dimensions of integration in interdisciplinary explanations of the origin of evolutionary novelty. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *44*(4), 537–550. https://doi.org/10.1016/j.shpsc.2013.09.008

MacArthur, R., & Wilson, E. O. (1967). *The Theory of Island Biogeography*. Princeton University Press.

MacLeod, M. (2018). What makes interdisciplinarity difficult? some consequences of domain specificity in interdisciplinary practice. *Synthese*, *195*(2), pp.697–720. https://doi.org/10.1007/s11229-016-1236-4

MacLeod, M., & Nagatsu, M. (2016). Model coupling in resource economics: conditions for effective interdisciplinary collaboration. *Philosophy of Science*, *83*(3), 412–433. https://doi.org/10.1086/685745

MacLeod, M., & Nagatsu, M. (2018, February). What does interdisciplinarity look like in practice: Mapping interdisciplinarity and its limits in the environmental sciences. *Studies in History and Philosophy of Science Part A*, *67*, pp.74–84. https://doi.org/10.1016/j.shpsa.2018.01.001

Mäki, U. (1992). On the method of isolation in economics. *Poznan Studies in the Philosophy of the Sciences and the Humanities*, *26*, 19–54.

Mäki, U. (2013). Scientific Imperialism: Difficulties in definition, identification, and assessment. *International Studies in the Philosophy of Science*, *27*(3), 325–339. https://doi.org/10.1080/02698595.2013.825496

Martin, L., Blossey, B., & Ellis, E. (2012). Mapping where ecologists work: Biases in the global distribution of terrestrial ecological observations. *Frontiers in Ecology and the Environment*, *10* (4), 195–201. https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/110154

Martinez-Alier, J., & Røpke, I. (eds). (2008). *Recent developments in ecological economics I*. Edward Elgar Publishing.

Mckibben, B. (1990). *The end of nature*. Viking.

Mendenhall, C., Karp, D., Meyer, C., Hadly, E., & Daily, G. (2013). Predicting biodiversity change and averting collapse in agricultural landscapes. *Nature*, *509*(7499), 213–217. https://doi.org/10.1038/nature13139

Mill, J. S., (1848) 2006. Principles of political economy. In Collected Works of John Stuart Mill, Vol. IIEd., J. M. Robson Liberty Fund.

Mitchell, S. (2003). *Biological complexity and integrative pluralism*. Cambridge University Press.

Mitchell, S. (2009). *Unsimple Truths*. University of Chicago Press.

Morgan, M. S. (2012). *The World in the model: how economists work and think*. Cambridge University Press.

Morgan, M. S., & Grüne-Yanoff, T. (2013). Modeling practices in the social and human sciences. *An Interdisciplinary Exchange. Perspectives on Science*, *21*(2), pp.143–156. https://www.mitpressjournals.org/doi/abs/10.1162/POSC_a_00089

O'Malley, M. A. (2013). When integration fails: Prokaryote phylogeny and the tree of life. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *44*(4), pp.551–562. https://doi.org/10.1016/j.shpsc.2012.10.003

O'Neill, R., & Kahn, J. (2000). Homo economies as a keystone species. *BioScience*, *50*(4), 333–336. https://doi.org/10.1641/0006-3568(2000)050[0333:HEAAKS]2.3.CO;2

O'Rourke, M., Crowley, S., & Gonnerman, C. (2016, April). On the nature of cross-disciplinary integration: A philosophical framework." Studies in history and philosophy of science part c. *Studies in History and Philosophy of Biological and Biomedical Sciences*, *56*, 62–70. https://doi.org/10.1016/j.shpsc.2015.10.003

Oppenheim, P., & Putnam, H. (1958). Unity of science as a working hypothesis. In: H. Feigl, M. Scriven, & G. Maxwell (Eds.), *Concepts, theories, and the mind-body problem* pp.3e36. The University of Minnesota Press.

Pelletier, F., & Coltman, D. (2018). Will human influences on evolutionary dynamics in the wild pervade the Anthropocene? *BMC Biology*, *16*(1), 7. https://doi.org/10.1186/s12915-017-0476-1

Pickett, S., Cadenasso, M., & Grove, J. (2005). Biocomplexity in coupled natural-human systems: a multidimensional framework. *Ecosystems*, *8*(3), 225–232. https://doi.org/10.1007/s10021-004-0098-7

Plutynski, A. (2013). "Cancer and the goals of integration.". *Studies in History and Philosophy of Biological and Biomedical Sciences*, *44*(4), 466–476. https://doi.org/10.1016/j.shpsc.2013.03.019

Purdy, J. (2015). *After nature: a politics for the Anthropocene*. Harvard University Press.

Ricardo, D. ((1817) 1951). *On the principles of political economy and taxation*, P. Sraffa edited by. (Works and Correspondence). Cambridge University Press.

Rice, C., & Smart, J., 2011.A Case Study of Evolutionary Economics. *Biology and Philosophy*, 26, 655–675.

Røpke, I. (2005). Trends in the development of ecological economics: from the late 1980s until the early 2000s. *Ecological Economics*, *55*(2), 262–290. https://doi.org/10.1016/j.ecolecon.2004.10.010

Rylance, R. (2015). Global funders to focus on interdisciplinarity. *Nature*, *525*(7569), 313–315. https://doi.org/10.1038/525313a

Sagoff, M. (2017). On the definition of ecology. *Biological Theory*, *12*(2), 85–98. https://doi.org/10.1007/s13752-017-0263-9

Schabas, M. (2005). *The Natural Origins of Economics*. Chicago University Press.

Settle, C., Crocker, T. D., & Shogren, J. F. (2002). "On the joint determination of biological and economic systems.". *Ecological Economics*, *42*(1–2), 301–311. https://doi.org/10.1016/S0921-8009(02)00105-2

Steffen, W., Crutzen, P., & McNeil, J. (2007). Are humans now overwhelming the great forces of nature. *AMBIO: A Journal of the Human Environment*, *36*(8), 614–621. https://doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2

Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. (2011). The Anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of Royal Society A*, *369*(1938), 842–867. https://doi.org/10.1098/rsta.2010.0327

Thomas, C. (2013). The Anthropocene could raise biological diversity. *Nature*, *502*(7469), 7. https://doi.org/10.1038/502007a

van den Bergh, J. C. J. M. (2001). Ecological economics: Themes, approaches, and differences with environmental economics. *Regional Environmental Change*, *2*(1), 13–23. https://doi.org/10.1007/s101130000020

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of the Earth'secosystems. *Science*, *277*(5325), 494–499. https://doi.org/10.1126/science.277.5325.494

Vogel, S. (2015). *Thinking like a mall: environmental philosophy after the end of nature*. MIT Press.

Voosen, P. (2016). Anthropocene pinned to postwar period. *Science*, *353*(6302), 852–853. https://doi.org/10.1126/science.353.6302.852

Wapner, P. (2010). *Living through the end of nature*. MIT Press.

Wätzold, F., Drechsler, M., Armstrong, C. W., Baumgärtner, S., Grimm, V., Huth, A., Perrings, C., Possingham, H. P., Shogren, J. F., Skonhoft, A., Verboom-Vasiljev, J., & Wissel, C. (2006). Ecological-economic modeling for biodiversity management: potential, pitfalls, and prospects. *Conservation Biology*, *20*(4), 1034–1041. https://doi.org/10.1111/j.1523-1739.2006.00353.x

Weisberg, M. (2007). Three kinds of idealization. *Journal of Philosophy*, *104*(12), 639–659. https://doi.org/10.5840/jphil20071041240

Worm, B., & Paine, R. (2016). Humans as a hyperkeystone species. *Trends in Ecology & Evolution*, *31*(8), 600–607. https://doi.org/10.1016/j.tree.2016.05.008

Zalasiewicz, J., Waters, C. N., Summerhayes, C. P., Wolfe, A. P., Barnosky, A. D., Cearreta, A., Crutzen, P., Ellis, E., Fairchild, I. J., Gałuszka, A., Haff, P., Hajdas, I., Head, M. J., Ivar Do Sul, J. A., Jeandel, C., Leinfelder, R., McNeill, J. R., Neal, C., Odada, E., Oreskes, N., & Williams, M. (2017, September). The working group on the Anthropocene: Summary of evidence and interim recommendations. *Anthropocene*, *19*, 55–60. https://doi.org/10.1016/j.ancene.2017.09.001