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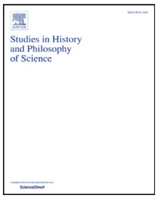

What does interdisciplinarity look like in practice: Mapping interdisciplinarity and its limits in the environmental sciences

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A B S T R A C T

In this paper we take a close look at current interdisciplinary modeling practices in the environmental sciences, and suggest that closer attention needs to be paid to the nature of scientific practices when investigating and planning interdisciplinarity. While interdisciplinarity is often portrayed as a medium of novel and transformative methodological work, current modeling strategies in the environmental sciences are conservative, avoiding methodological conflict, while confining interdisciplinary interactions to a relatively small set of pre-existing modeling frameworks and strategies (a process we call *crystallization*). We argue that such practices can be rationalized as responses in part to *cognitive constraints* which restrict interdisciplinary work. We identify four salient integrative modeling strategies in environmental sciences, and argue that this crystallization, while contradicting somewhat the novel goals many have for interdisciplinarity, makes sense when considered in the light of common disciplinary practices and cognitive constraints. These results provide cause to rethink in more concrete methodological terms what interdisciplinarity amounts to, and what kinds of interdisciplinarity are obtainable in the environmental sciences and elsewhere.

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1. Introduction

Interdisciplinarity (ID)[1] has been called upon to address a wide range of pressing environmental problems on the grounds that social, economic, ecological and climate systems are causally entwined. Solving these problems, it is thought, requires conceptually or methodologically integrated approaches from multiple social and natural sciences, and may also require the participation of extra-academic stakeholders (see Klein et al., 2012). There is thus a strong policy interest in promoting and funding collaboration among ecologists, economists, sociologists, civil engineers, atmospheric scientists and many others working on environmental problems. However, despite a large and still growing literature on the subject of interdisciplinarity, it remains uncertain how interdisciplinary work between fields like these can be cognitively structured in order to achieve gainful interdisciplinary responses to resource management and other environmental problems.

Much current literature characterizes (and often defines) “interdisciplinary” (ID) interactions as localized problem-driven interactions which result in novel and transformative methodological and conceptual developments (see Huutoniemi, Klein, Bruun, & Hukkinen, 2010 for an overview of how “interdisciplinarity” is understood in the literature). However, we will show here that in the case of environmental sciences much cross-border modeling is conservative, making use of pre-existing methodological frameworks. Rather than exhibiting substantial methodological innovation and diversification, interdisciplinary practices are *crystallizing* around four principal integrative methodological platforms - each of which we describe here. Each has various *interdisciplinary affordances*. These affordances help explain the effectiveness of these frameworks in bridging the institutional and cognitive constraints which generally inhibit interdisciplinarity in the environmental sciences. We will argue that crystallization of this kind is not a counter-intuitive phenomenon, however much it might run counter to the normative methodological assumptions or expectations of interdisciplinarity scholars. It can be understood as a rather natural attempt to build well-structured interdisciplinary interactions around a limited set of manageable modeling frameworks and strategies in a similar way to which participating fields

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[1] Throughout the paper, we will abbreviate both the noun “interdisciplinarity” and adjective “interdisciplinary” as “ID”.

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themselves internally structure their own practices around such frameworks and strategies (see Humphreys, 2004).

These lessons from scientific practice suggest that there is cause to be more cautious or more strategic about how interdisciplinarity is managed and implemented, and what we can reasonably expect from it.[2] The current presumption that interdisciplinarity needs highly problem-driven contexts requiring fundamentally novel conceptual solutions and methodological approaches should be weighed against our findings that the crystallizing strategies of interdisciplinary practice are more consistent with traditional models of scientific discovery. Such models favor incremental development by building from well-established mathematical frameworks, and adjusting concepts and methods at the outer edges of fields. Such techniques avoid disruption to fields but put them in a good position to develop solid cross-border collaboration or integration now and in the future.

The paper proceeds as follows: the following section provides a general background concerning increasing expectations of interdisciplinary research. Section 3 discusses a more specific context in which interdisciplinary research is demanded in the environmental sciences as a result of increasing interactions between natural and social systems, which have traditionally been studied separately. Section 4 offers our typology of emerging ID modeling strategies, namely, data-driven modeling, modular model-coupling, integral modeling, and substitutive model-coupling, drawing on our ongoing case study. Section 5 draws several methodological lessons for interdisciplinarity based on our findings, and more generally argues for the importance of understanding scientific practice in order to prescribe how to conduct interdisciplinary research. Section 6 concludes by summarizing our argument.

2. Expectations of interdisciplinarity (ID)

Over the last 20 years or so interdisciplinarity (ID) has been widely discussed in science policy, science studies and education science. Much of this discussion is strongly favorable towards ID, seeing it as essential to resolving 21st century environmental, social and health problems, while perceiving the institutional and cognitive rigidity of established disciplines as obstacles to effectively resolving such problems. New approaches are required, and ID interactions (whether collaborative or otherwise) are seen as the medium through which such approaches can be developed. As a result, an important imperative has been placed on identifying "genuine" ID interactions which achieve these goals, from those that do not, particularly for research funding purposes (see Huutoniemi et al., 2010).

However, agreeing on a definition of ID which can distinguish genuine ID interactions from other kinds of cross border interactions or exchanges, such as multidisciplinary or even imperialistic (Mäki, 2013) ones, has proved difficult. Indeed a major focus of ID studies has been on taxonomizing different ways interdisciplinarity and multidisciplinarity can be conceptualized or occur in practice (Klein, 2010). Scientists are by no means united themselves on what they might mean by it (see Aboelela et al., 2006). The broadest encompassing definitions do not take a stance on what kinds of activities or interactions ID consists of. Klein (1990, p. 196), for instance, gives the following general definition: "Interdisciplinarity is a means of solving problems and answering questions that cannot be satisfactorily addressed using single methods or approaches."

Within this many activities could be considered interdisciplinary. However, in recent years a predominant view has formed around the expectation that genuine ID requires *integration* (see Lattuca, 2003). That is, interdisciplinarity is,

> a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession … [by] draw[ing] upon disciplinary perspectives and integrat[ing] their insights through construction of a more comprehensive perspective. (Klein & Newell, 1997, pp. 393-394)

The National Academy of Sciences (2006) gives a similar definition, according to which interdisciplinarity is:

> "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."

ID interactions are integrative to the extent that methodological and conceptual frameworks or other disciplinary resources from separate disciplines and fields are integrated in order to solve a problem. In theory, integration serves to distinguish ID from multidisciplinarity. In multidisciplinary contexts researchers simply break up a problem into parts recognizable as disciplinary problems, and go away and solve those parts separately without forging any real connections between their approaches. Integration and similar concepts are, however, often cashed out in the relevant literature in term of metaphors rather than harder methodological or conceptual criteria. Klein (2010) cites a range of "key descriptors" applied to describe ID; "integrating", "interacting", "linking", "focusing" and "blending".[3] Other popular metaphors include "boundary crossing" or "bridge building" or "bilingualism" (Repko, Szostak, & Buchberger, 2016). Multidisciplinarity in contrast is associated with phrases such as "juxtaposing", "sequencing" or "coordinating". "Integration" itself however remains arguably vague (although see O'Rourke, Crowley, and Gonnerman (2016) for some philosophical attempt to clarify the concept using cases from biology).

While many notions of ID treat integration as the crux of ID, some concepts require more, often motivated by the strong normative stances authors take towards ID, and what they expect from it. Two additional requirements, or at least expectations, stand out in this regard. The first is that proper ID requires earnest attempts to address real-world problems. The motivation for this relates to the objectives many have for ID in the first place, and/or the conditions required for prompting integration. ID research or problem-solving should be applied to outward-looking research and problem-solving work, rather than being inwardly directed at questions or problems framed within disciplinary contexts. Further, real-world problem-solving contexts create the pressure for ID interaction insofar as real-world problems cannot be reduced to one discipline's methods, concepts, etc. Such problems are complex and cross disciplinary boundaries (Repko et al., 2016). Hence there is an expectation that real-world problem-solving prompts or

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[2] Some sociologists are critical of the current policy discourses on interdisciplinarity based on their analyses of institutional dimensions of interdisciplinary research. See, e.g., Callard and Fitzgerald (2015) and Frickel, Albert and Prainsack (2016). Our approach is distinctive from but complementary to this literature.

[3] Another philosophically relevant dimension of ID concerns *epistemic interdependence* between collaborators from different fields or disciplines and trust among them (see e.g. Andersen, 2013).

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necessitates integration in ways other contexts cannot. It is worth noting that these ideas that ID is or should be problem-driven fits common patterns of 3–5 year short-term funding schemes which often form the basis by which ID is institutionally sponsored. Such funding schemes require scientists and engineers to come together in the context of applying for funding to solve a specific real world problem, and provide a plan for an integrated solution over that period.

The second additional criterion for ID is implicit in the concept of a “comprehensive perspective” in Klein and Newell (1997, pp. 393–415) definition above. There is a common expectation that, whatever integration entails, the result should be in some sense novel and transformative for the fields involved, resulting in new concepts and practices (Huutoniemi et al., 2010), or an overall more holistic or systematic understanding of a set of phenomena or the problems being addressed. One commonly stated implication is that it is insufficient to just piece together methods and concepts from different fields without any novel practices emerging. If such a requirement is used to help define integration for the purposes of ID, then this creates a very high standard, which, as we will see, is probably not often achieved in the environmental sciences, nor elsewhere. The motivation for such a standard derives from the supposedly *disruptive* aims of ID (see conceptions in particular of “Mode 2” or “post-normal” science) and the envisioned need to break up disciplinary structures and open up scientific disciplines to other points of view (Funtowicz & Ravetz, 1993; Nowotny, Scott, Gibbons, & Scott, 2001). But it is also an extension again of the idea that disciplinary approaches are insufficient for real-world problems even when jointly applied to a problem. Interactions in which disciplinary practices and structures are not disrupted or reformed are thus sometimes considered the hallmark of multidisciplinary ones. Practitioners who are critical about the standard methodological framework of economics for instance tend to concur with this view (e.g. Berg & Gigerenzer, 2010; Costanza et al., 2014). Ecological economics is thus sometimes understood as an attempt to create just such a genuinely ID approach.

It is somewhat difficult to know whether these criteria are considered actual requirements of true or proper ID, or simply expectations of what integrative interactions will produce and in what contexts this will happen. Either way, they both add a degree of “normative baggage” to the discussions surrounding ID. We find both criteria are out of step with current scientific practice and do not reflect how ID commonly occurs in the domain of model-building in the environmental sciences, which are arguably inherently interdisciplinary and oriented towards real-world problem-solving. As we show in this paper, many interactions that are otherwise integrative fail to produce novel methodological or conceptual transformations. Our diagnosis is that these expectations surrounding ID are not well aligned with what is generally feasible given the constraints under which scientific researchers work, particularly in the context of short term grants. In fact, while the institutional constraints inhibiting ID work (such as peer review, tenure promotion and the like; see Jacobs & Frickel, 2009) are well understood, cognitive constraints on ID research are not (Brister, 2016; MacLeod, 2016).

In other contexts, MacLeod and Nagatsu (2016), and MacLeod (2016) have analyzed the cognitive constraints affecting economics/ecology interactions and engineer/molecular biologist interactions in systems biology, arguing that these constraints should not be underestimated. Cognitive constraints include, for instance, different evidential standards and epistemic values, different modeling and experimental practices, inconsistent concepts, and the overall opacity of practices due to their complexity. Brister (2016), in her own study of interactions between conservation biologists and anthropologists, identifies similar constraints afflicting relations between natural and social scientists. Further, she notes that disciplines often preclude productive ID interaction by framing problems in terms of their own specific methodologies and specific values. All of these restrict ID researchers from finding ways to coordinate their practices, let alone to produce novel integrated methodological or conceptual transformations.

Generally, the cognitive constraints confronting ID interactions are at risk of trivialization when presented as “communication problems” as they often are (Brister, 2016; MacLeod, 2016). These constraints often arise out of deep epistemological disputes rooted in the nature of practices within fields. One reason many of these methodological differences in assumptions, concepts and values are so hard to resolve is that they occur upstream in the problem-solving systems upon which fields rely. Such systems have been optimized over time to solve particular classes of problems. This makes such differences difficult to remove without requiring substantial, and often impractical changes elsewhere to these systems.

To build the case for a more nuanced practice-driven understanding of ID, we describe.

The current modeling strategies which are chosen in the environmental sciences for ID modeling, and why they are chosen. In particular, we evaluate *interdisciplinary affordances* and *gains* of these modeling strategies. MacLeod and Nagatsu (2016) define *collaborative affordances* as the features of a methodological strategy which provide collaborators with means to overcome ID constraints and despite them coordinate and integrate their scientific practices and scientific resources (model-building, experimentation, epistemic values and standards etc). However, ID in the environmental sciences is not always collaborative. Some levels of integration happen purely within one field alone, when researchers build models for instance that incorporate resources from a number of other fields. This happens in the environmental sciences to some degree. Hence it’s worth assessing strategies generally in terms of their overall *interdisciplinary affordances*, features which facilitate integration in the face of constraints, which can include affordances for collaboration.

This investigation reveals two important facts. First, relatively few patterns of interaction dominate the ways in which modelers in the environmental sciences choose to interact. These modes of interaction are based on a limited set of modeling templates. Second, the choice of these modes can be understood to some extent as responses to cognitive constraints. That is, their interdisciplinary affordances reside for the most part in their *minimization of novel methodological or conceptual invention*. We will further discuss implications of these findings on the conservative nature of ID practices in Section 5.

3. Nature-society interactions: ID in the environmental sciences and its constraints

Before moving on to consider these patterns of interaction, however, it is worthwhile giving some introduction to the background context and motivation for interdisciplinarity in the environmental sciences. ID is seen by many as essential to modern environmental science: contemporary environmental problems are complex and the environmental, social or other demands we have of solutions often diverse and multifaceted. Such solutions arguably reside outside the reach of classical disciplinary problem-solving frameworks (DesRoches, Inkpen, & Green, forthcoming). Solutions to these problems require understanding of both natural and social systems, and how these systems interact (cf. Coupled Human and Natural Systems, CHANS: Liu et al., 2007; the Anthropocene:

Crutzen, 2006).[4] Civil/environmental engineers, economists, ecologists, atmospheric scientists, sociologists, urban planners and others find themselves under pressure from funding agencies to collaborate.

While it is impossible to develop an overall account of how successful ID interactions have proved in the environmental sciences, despite the funding and other institutional incentives devoted to them, published studies indicate that it is not always smooth sailing. Certainly collaboration has proved difficult between mainstream economists and ecologists, and between qualitative social scientists and any quantitative environmental science or engineering field (see for instance Roy et al., 2013; Strang, 2009; Brister, 2016; Fox et al., 2006). To obtain original data on economics-ecology interactions, since 2014 we have conducted 14 semi-structured interviews with 13 individuals (6 economists, 5 ecologists and 2 sociologists) working in interdisciplinary projects on forestry, fisheries and water management, as well as on environmental protection. We have additionally attended and recorded 4 research meetings in one bio-economic lab. From this data set, together with other methodological articles written by ID practitioners themselves, we have identified several important cognitive constraints as major difficulties governing interactions between economists and ecologists.[5]

In the first place, for instance, economics and ecology build models and design experiments at different temporal and spatial scales which reflect the different scales at which important ecological and economics phenomena occur and which are practical to study given each field's goals (Wätzold et al., 2006; Stevens, Fraser, Mitchley, & Thomas, 2007). While economics focuses on administrative-level equilibria useful for economic policy, ecological experiments or observational studies tend to focus on much smaller geographic areas which can be effectively controlled or measured.[6] Economics and ecology are also divided in terms of the time scales at which they consider their respective systems can be effectively studied. In economics equilibrium analysis typically pays little or no attention to the speed of the process in response to shocks for example, and the dynamics is assumed to operate over short time scales (or no time at all). Ecological dynamics operate in contrast over much longer time scales. Models built in economics and ecology for both these reasons are commonly not in spatial or temporal alignment. As Stevens et al. (2007) stress, scaling up experiments in ecology is far from trivial for methodological and practical reasons. Likewise building multiscale models which can integrate models built at different spatial or temporal scales raises a wealth of its own methodological challenges, and remains particularly difficult to do without large assumptions which weaken the validity of the outcomes.

Further, as documented by Armsworth, Gaston, Hanley, and Ruffell (2009),[7] economists and ecologists differ highly over various evidential standards and epistemic values, particularly over the legitimacy of statistics in model-building. Economists are according to them more theory-driven, ecologists more data-driven. The goal of canonical economic research is to derive and test theoretical models. The role of statistical regression in economics is confined to testing these models. These practices help “define” the proper role of techniques like statistical regression within the field. Ecologists however will use data to generate models through statistical techniques, employing these models without deeper theoretical foundations.[8] Economists employ data to test the validity of their theoretical models and test for “off-model” relationships, rather than using the data as a source of such relations. These divergent modeling practices and standards, Armsworth et al. (2009) report, can breed conflict and create obstacles to interactions between ecologists and economists who may disagree fundamentally over what are reliable and effective approaches for solving a given environmental problem. Data-driven approaches in ecology can be seen as unproductive and uninformative from an economic point of view, whereas the commitment economists display towards established theory and problem-solving frameworks like constrained optimization (which ecologists readily challenge) may be seen as narrow and limited. In general neoclassical economic concepts and problem-solving frameworks can seem too simplistic and unjustifiable outside economics.

While open-minded researchers can and do attempt to work around these problems, some of the intransigence of these obstacles stems from the centrality of these standards to the fields. Many mathematical modeling templates and experimental techniques have been designed around them, and as a result, the skills and expertise economists and ecologists have, including the ability to assess what counts as good or bad research, cannot be easily reapplied under different sets of governing standards. Using popular terms in cognitive science and biology, researchers' cognitive tasks are *scaffolded* by basic conceptual and methodological resources, which are heavily adapted to the problem-space of a given field. These cognitive scaffolds in turn affect what researchers see as a problem and how to solve it. Such *epistemic niches* (Sterelny, 2010) are built around a set of epistemic standards or basic conceptualizations of phenomena that are often at odds with those of another field. Sometimes such standards or fundamental concepts may well be incommensurable and thus technically impossible to bridge without large scale reformation of deeply embedded upstream principles (see Longino, 2013). For example, DesRoches et al., (forthcoming) point out that historically entrenched ontologies of natural versus artificial (or anthropogenic) causal factors reinforce “proper” domains of investigation for each field and get in the way of more unifying conceptualizations. Such ontological divides can count strongly against any deep collaborative synthesis between ecology and economics.

In addition, another fundamental difference, namely the differences in non-epistemic value-orientation in different fields, may give rise to incommensurable practices. For example, mainstream environmental economics adopts anthropocentric views, while ecological economics (and perhaps implicitly ecology too) adopts biocentric views. This difference manifests itself in the different extents to which natural capital is seen as substitutable with other capitals, or the different methods and concepts by which ecosystem services are valued (see Costanza et al., 2014). Even within social sciences, which are broadly anthropocentric, economists' one-dimensional utility theory and sociologists' more pluralistic views can lead to incommensurable evaluations of net impacts of

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[4] Ecological economics, which emphasizes the finite and unsubstitutable nature of biosphere as capital, is a prominent interdisciplinary field, but our focus includes a wider range of fields that model interactions between natural and human systems in the environmental sciences without any commitment to particular theories of sustainability, such as a theory of steady-state economy.

[5] All recordings except lab meetings have been transcribed into texts. For more details about empirical data collected before 2016, see MacLeod and Nagatsu (2016).

[6] Scale misalignments between economics and ecology can take another form. A salient example is economics focusing on a state level (trade deficits etc.) while climate change models concern global change.

[7] This article appears in a special profile of *Journal of Applied Ecology* on “integrating ecology and the social sciences” (2009, volume 46, issue 2), which includes several relevant discussions on economics-ecology integration (e.g., Lowe et al., 2009).

[8] The tension between theory-driven and data-driven approaches sometimes manifest itself also within economics, for example in the controversy over ‘mostly harmless econometrics’ (Angrist & Pischke, 2008).

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different policies on the environment and society. Since such non-epistemic values are embedded in epistemic scientific practices (in terms of concepts, models and methods), it is often difficult to even identify the exact nature of disagreements among practitioners.

In general, all these differences in modeling scales, epistemic and non-epistemic values and standards, and ontological assumptions create entrenched conceptual and epistemological gaps between fields, which entrench both incompatible methodologies and practices but also a degree of opacity.[9] Opacity arises when the dependencies of another field on certain conceptual notions and evidential standards and practices may be hard to identify, not to mention justify, from outside the field. This makes it hard for collaborators to figure out what kinds of alterations would be considered reliable and productive for both parties, and practical given the resources each field has.

Having said all this, it is worth pointing out that the cognitive gaps between economics and ecology, and among other environmental science fields, are not always as substantial. For example theory-driven approaches are common in physics or chemistry-based environmental sciences such as atmospheric sciences and hydrological sciences. The boundaries of those fields from one another are a lot clearer, and less likely to be in conflict. Nonetheless scale problems do frequently arise to the extent that economic models for instance generally lack the resolution and complexity of models in many other natural environmental science fields like hydrology (Voinov & Shugart, 2013). Furthermore, there are shared gaps between quantitative environmental science fields and non-mathematical social science approaches, particularly those from sociology. Indeed the cognitive boundaries separating economics and ecology are to some degree lower than those separating sociologists from ecologists, as the former two share a "positivistic and quantitative orientation" (Lowe, Whitman, & Phillipson, 2009, p. 301). Sociologists have had in general a hard time convincing economists, ecologists and others of the viability of their interpretive and qualitative, or purely statistical, approaches, and finding ways to integrate these approaches with the mathematical models quantitative environmental scientists tend to build.[10] (See 4.1 in the next section as a strategy to solve this problem.)

While we do not want to give the impression that collaborations in the environmental sciences, and particularly economics and ecology are impossible, we do think that the breadth of the cognitive constraints these researchers face have been underestimated in ID scholarship in general. Cognitive obstacles of various forms are ever-present in ID work in the environmental sciences, in addition to institutional ones. As such, any particular strategy collaborators (or integrators) employ can be evaluated in terms of the features it possesses which help facilitate.

Interdisciplinary interactions on a problem. We refer to these features as *interdisciplinary affordances*. In the next section we look at the dominant strategies environmental scientists are currently employing, and analyze these strategies with respect to their interdisciplinary affordances.

4. ID modeling strategies

Given the expectations many interdisciplinarity scholars have about ID, it may come as some surprise how limited it often may be. Analysis of our interviews with scientists, as well as the literature by participants themselves of practices within this context, reveal that the majority of modeling strategies can be grouped into four main categories: data-driven modeling, modular model coupling, integral modeling, and substitutive modeling.[11] These strategies are all integrative in one sense or another. In other words, these strategies jointly provide a more concrete meaning to the term 'integration' which is often unanalyzed in the ID literature.

4.1. Data-driven modeling strategies

Interdisciplinary data-driven strategies employ a statistical modeling platform like multiple regression analysis or other kinds of statistical inferential processes to construct relations between variables. Different fields contribute their own individual data sets, and the chosen data analysis method enables connections to be made between variables which are not all normally measured, or capable of being measured, within a single field. Some forms of Bayesian network analysis can be useful in this context. Different collaborators can contribute a set of variables to help build a map of causal dependencies relevant to a given management problem and a set of priors governing the relations. These relations can then be updated based on the data the collaborators provide. Bayesian analysis relies on initial estimations of the relations between variables, which can be theoretically derived from the fields involved (using a model for instance), but in principle Bayesian analysis is neutral with respect to where that information comes from or how it is derived (e.g., see Haapasaari & Karjalainen, 2010 for the use of expert knowledge). The Bayesian process ultimately estimates the relationship through iterations using the available data.

The fact that these methods need involve few methodological or theoretical commitments from the participants or any deeper more domain-specific modeling procedures and methods enables relatively straightforward interdisciplinary interaction. Researchers can bring their data, sets of variables, and in the case of Bayesian network modeling, background expectations to the table. One benefit is that non-mathematical researchers like sociologists have a reasonable opportunity to contribute their data to such modeling frameworks (Haapasaari, Kulmala, & Kuikka, 2012). Overall these kinds of strategies have rather high interdisciplinary (more specifically collaborative) affordances and produce a collectively constructed model which does not need to prefer one field's method or theory over another (although of course there is a positivistic bias to such an approach). Alternatively, of course, the theoretically and methodologically shallow aspects of these kinds of schemes may not be acceptable to everyone involved as we noted in the case of regression analysis above (Armsworth et al., 2009). Consider one case study for instance on the application of a Bayesian Belief Network analysis, which was employed to analyze management scenarios for Baltic salmon fisheries. Haapasaari et al. (2012, p. 5) report that the economists "did not believe in the possibilities of Bayesian belief networks in dynamic optimization" and instead opted for a more traditional model of natural resource economics.

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[9] Phenomenologists use the term *transparency* to describe how the agent subjectively experiences well-entrenched external scaffolds (e.g. shoes or iphones) that individualize her interactions with the world (Sterelny, 2010). A disciplinary scientist may similarly experience her concepts and methods as well as material scaffolds (e.g. microscopes or statistical packages) as transparent. To outsiders, this implies opacity.

[10] In one of the interviews with an ecologist working in an interdisciplinary project involving ecologists, economists and other social scientists, he expressed some frustration with social sciences claiming "there is nothing like truth" in social science, in contrast to natural sciences. The interviewee complained that his collaborating social scientists did not care about consistency between his mathematical model and their written texts. (interview on 30 May 2014).

[11] For this framework we have relied partially on Voinov and Shugart (2013), particularly for the concept of integral modeling, although we have expanded on the class of models they refer to as integrated. Kelly et al. (2013), through an exhaustive study, distinguish five "modeling approaches" currently used in integrated environmental assessment and management. Since our interest is specifically how different strategies handle cognitive constraints, rather than models or mathematical types, our categorization tends to cross-cut theirs.

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The economist, when interviewed by us (conducted on 8 December 2015) rather attributed the problem to a large cognitive gap rather than conflict of belief or epistemic value, suggesting that the problem was due to the difficulty of making a particular discrete Bayesian model using a particular software compatible with dynamic optimization within the time-frame of a PhD project. Either way aligning the two approaches can be very difficult. Economists typically measure profit or utility (based on individual preferences) as the only criterion, and identify a policy measure that maximizes profit or utility under given constraints. In contrast, the Bayesian Belief Network analysis typically adopts scenario-based decision analysis, using heterogeneous utility concepts (such as economic, social, recreational, and ecological utilities) and weighing them against each other on a case-by-case basis.[12] Given the centrality of utility maximization in economics (and its commitment to normative individualism as the principle of anthropocentric valuation), weighing it against other kinds of utility, whose origins are opaque, may seem arbitrary and unjustified.[13] In sum, while data-driven modeling strategies have high collaborative affordances, providing a framework for integrating information from disparate fields, their theoretical neutrality and openness to multiple perspectives can be an obstacle.

4.2. *Integral modeling*

Integral modeling (a term we borrow from Voinov & Shugart, 2013) employs a particular *domain-neutral* modeling framework to combine information from different fields. By domain-neutral, we mean that these modeling structures are similar to data-driven practices, providing a schema or template for relating any variables (whatever their disciplinary origin) in complex systems and underlying methodologies for analyzing those models. We include here for instance agent-based models (ABM) and system dynamics models (SD). Both are employed in the environmental sciences as a means to integrate different fields. We concentrate here on SD models. System dynamics modeling has for instance long played a prominent role in ID and environmental science scholarship by being consistently seen to embody the kind of methodological structure and philosophical attitudes required to capture complex environmental interactions which cross disciplinary boundaries.[14] Generally system dynamics models relate variables through sets of coupled differential equations. These equation represent what are commonly referred to in the environmental sciences as stock-flow relationships, i.e. both the quantity of a given stock and its flow or rate of change at a given point in time. Such models track the movement of stocks (resources) around a system. Importantly system dynamics models can easily build in complex interactions between variables (in ways not necessarily available in modular model-coupling cases (see 4.3)), such as feedback relations and time-scale variances (although spatial variables rarely feature). Not only do modelers provide variables as in the case of data-driven modeling, but also they provide models governing the relationships between those variables.

As with the other cases, these integral modeling strategies provide particular interdisciplinary affordances, handling certain cognitive obstacles well. Issues of model and methodological compatibility are avoided, since a common modeling platform is used, although unlike the case of data-driven modeling, a causal-mechanistic model is the outcome, which can serve to provide richer insight into the phenomena in question. The methodological standards to be applied to parametrize, validate and analyze the model are driven to a certain extent by the modeling paradigm, avoiding potential methodological conflicts, at least amongst those who sign up to participate on building such models.

This all said, integral models (e.g. system dynamics or agent-based models) do not currently serve as platforms for collaborative interaction, though they serve as platforms for integration.[15] Their collaborative affordances seem limited. We speculate on some of the reasons here. Most models seem to be generated within a single field, which borrows variables and data from other fields and models elements to describe interactions between variables. As a result, there are likely disciplinary biases and standards built into such models which restrict their ability to prove credible or informative outside their discipline. The difficulty of performing such an integration over a wide range of fields may in fact help explain why these models are usually constructed within a field. Doing so avoids need to standardize complex independently developed models so that they are interpretable within one software language, the challenge modular-model coupling faces (4.3 below). Yet lack of actual collaboration, and indeed computational limits, restricts the detail and complexity of the representations of interactions between variables modelers bring into SD or AB models from outside their field. This might well serve to make such models seem less credible and useful to outsiders, and only credible to insiders who believe strongly in the ability of systems dynamics and agent-based models, though relatively simple interactions, to represent and account for complex emergent behavior.[16] As Kelly et al. (2013) observe, SD models are mostly limited to analyzing coarse scale trends, which may not always seem useful or valuable to outsiders.[17] Integral modeling thus creates its own obstacles to ID collaboration, even if it can to some extent serve as a platform of ID integration.

4.3. *Modular model-coupling*

Modular-Model Coupling[18] is perhaps the predominant form of integrative modeling used currently in the environmental sciences, and represents a highly canonical form of interdisciplinary modeling. In this strategy each discipline provides a model to be

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[12] Only 2 out of 15 publications assigned to the category of "Bayesian Networks" in Kelly et al. (2013, pp. 166-7) adopt optimization of a single objective function in addition to scenario-based analysis.

[13] In fact, multi-criteria decision analysis (MCDA), such as multi-attribute utility theory, is increasingly popular in environmental sciences (see Huang, Keisler, & Linkov, 2011 for a review), and applied environmental economists may be more open-minded than we suggest here. However, as one economics PhD student we interviewed (on 3rd June 2016) informed us, mastering sophisticated constrained optimization is a full-time PhD job, which naturally makes early-career economists reluctant to engage with alternative methods such as scenario analysis given the time constraints.

[14] In fact system dynamics is often seen to embody the required attitudes for *being* interdisciplinary, given its common interpretation as a non-reductionistic methodology (see Farrell, Luzzati, & Van den Hove, 2013).

[15] According to Voinov and Shugart (2013) most ABM and SD models are currently built in-house. This is borne out through a close examination of the list of publications assigned to those categories by Kelly et al. (2013). Furthermore, ABM and SD models have been used restrictively so far, ABM models principally in land-management, and SD models in water-management.

[16] Lehtinen and Kuorikoski (2007), for example, argue that economists do not use agent-based models because these models do not fit their ideal of understanding, which is based on analytic derivation through equilibrium analysis.

[17] A coarse-grained mechanistic understanding is useful for the intuitive understanding of the general system in question, and for communicating its characteristics to stakeholders, rather than for providing specific predictions about the behavior of particular systems in particular times and locations.

[18] It is also called coupled-component modeling by Kelly et al. (2013) and plain "integrative" modeling by Voinov and Shugart (2013). We prefer "modular-model" coupling to emphasize the degree of modularity of modeling components preserved in these modeling strategies.

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assembled with other models. Output variables from component models serve as input to other component models. These models feed relevant information to one another. The resulting system is calibrated to meet the constraints of a problem and the available data. For example, Strasser et al. (2014) report on developing a large-scale integrated model to assess the effects of climate change on the economic viability of skiing resorts in the Austrian Alps. The integrated models combine a climate model, estimating future climate change, and a snow cover evolution model drawing on the climate change model to estimate future technical snow production requirements and its efficiency, water and energy consumption. Additionally the snow production model feeds information to an economic model analyzing the costs and benefits of snow production, and a tourism model, modeling regional tourism structure, for policy analysis. Both of these latter models also feed information to one another. Building each of these models and integrating them required an interdisciplinary team of climate scientists, snow hydrologists, economists, tourism researchers and stakeholders.

For the most part researchers building such models generally contribute what are commonly called "legacy" models (Voinov & Shugart, 2013) to model-coupling projects, and rely on established methodologies associated with such models in order to apply them to specific scenarios; hence the modularity of this approach. This does not mean however that such models are simply plugged together. Getting models from different fields to operate together requires substantial integrative processes, as Strasser et al. (2014) emphasize, including the selection of appropriate interfacing tools, which can link models often formulated in different computational languages, the selection of mathematical methods to link models of different spatial or temporal scale, and agreement upon epistemic and other values for deriving and measuring model outcomes in order to address the management problem. While this is often difficult work, a critical affordance of modular model-coupling comes from the degree to which established disciplinary practices are nonetheless preserved. Individual disciplinary researchers remain responsible for their components, and for assessing the reliability, theoretical value and other standards of the components they provide. The substantial work of building new models, which somehow integrate methods and concepts from the background fields, is thus avoided, and the main work is the boundary work of re-applying and connecting pre-existing models.[19]

The gain of such collaborative endeavours can be quite significant, in terms of what interdisciplinarity can bring to a problem. Instead of modelers having to make strong assumptions or simplifications about systems or processes that lie outside their expertise, theoretically well-motivated and established models can be provided, which have greater robustness, and thus allow, say, optimization or scenario-based management strategies to explore relationships and sensitivity amongst a large range of environmentally significant variables.

More reliably and with more theoretical depth than data-driven and integral methods can achieve. On the other hand, there are trade-offs, as Voinov and Shugart (2013) report. While data-driven and integral modeling may to some extent side-step scale issues and the domain-specific theoretical and methodological dependencies of most models, modular model-coupling often runs hard up against both. Contributed models are generally designed for goals and scales specific to the fields they originate from, and their performances are evaluated relative to these goals (Bennett et al., 2013). Reapplying them to problems outside their design specifications may push them outside their proper range of validity. Handling scale problems is usually most easily addressed through aggregation and averaging procedures which introduce error, and tend to ignore the possibilities of feedback. Further combining complex models can lead to an even more complex integrated model, which is extremely difficult to calibrate and to interpret. Voinov and Shugart (2013, p. 151) refer to such constructions as "integronsters", which are "perfectly valid as software products but ugly and useless as models". Such modeling strategies may technically give answers to overriding problems, but provide very little means for understanding the causes governing the solution, and thus for generating general theoretical principles or insight into these solutions.

4.4. Substitutive model-coupling

The last category is the least observed of those above, but perhaps the most interesting from an interdisciplinary point of view. 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. We have studied closely interactions between ecologists and economists addressing renewable natural resource management problems. Ecologists and economists have long employed similar modeling frameworks to handle these problems. The frameworks composed by each contain a biological growth model component and an economic optimization component. The growth model is traditionally represented in economics using simplified, non-mechanistic biomass representations of the resource (like tree or fish stocks) and its growth rates. Ecologists can employ much more sophisticated representations, such as process-based models, which capture a range of variables which affect growth. On the other hand ecologists use what economists would consider unreflective optimization criteria, with a history of relying on *maximum sustained yield* (MSY), without any considerations of economic variables like costs and prices, as well as discounting of future value. Economists instead use as a management goal the *maximum economic yield* (MEY), i.e., net present value of a given stock taking costs and prices into account (see Binkley, 1987 for forestry; Grafton, Kompas, & Hilborn, 2007 for fishery). As such, these modeling frameworks can be integrated by swapping out unsophisticated components for the more sophisticated ones collaborators can provide.

This strategy has proven so far to be a very useful collaborative platform. The strategy can leverage off pre-existing relations between variables to join components, with those variables (like population numbers) already playing the role of linking components in the original disciplinary modeling frameworks. Since for the most part the components are already in spatial and temporal alignment within the existing frameworks, scale problems do not arise. Furthermore model construction tasks largely remain within the domain of each field, and thus under governance of their own methods and standards. Since the modeling components are well-integrated and relationships clear, feedback between components can be used to help better design components using information from across disciplinary boundaries. MacLeod and Nagatsu (2016), for instance, report a case in which the economic optimization algorithms were able to find errors in the underlying growth model (discontinuities for instance), which were sent back to the ecologists and ultimately used to correct and improve the growth model.

Naturally, however, while such an approach has quite clear interdisciplinary (and in particular collaborative) affordances, its

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[19] This requires distinct software development expertise, which is not necessarily related to any substantial fields. See, e.g., Brown et al. (2014) for software-related issues discussed in agricultural science, in which multiple software platforms are developed to connect crop genetics models, soil models, etc.

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feasibility depends on particular circumstances being in place, namely the existence of homologous modeling frameworks. These are likely to be uncommon, although perhaps not so rare given histories of model sharing, and the overall finite set of mathematical systems in operation in science, according to Humphreys (2004). In addition, field-specific factors may complicate the judgement about which models are more naive and thus should be substituted. For example, fisheries science has a long history of using MSY as the management objective for various reasons (see Smith and Punt 2001) and it is still being used as the EU fishery policy objectives for example, and economists have yet to convince fisheries scientists and policy makers to switch to MEY (see Grafton et al., 2007 as a recent attempt).[20] These field-specific factors include non-cognitive obstacles including differences in values and institutions, and cannot be resolved through successful integrative modeling alone.

5. Lessons for interdisciplinarity: crystallization and the importance of understanding scientific practice

The strategies we have discussed above have several important characteristics with ramifications for discussions and normative expectations of interdisciplinarity in the environmental sciences and beyond. In the first place, analyzing ID practices in terms of strategies like these provides a more concrete methodological understanding of what ID is or how it manifests itself in a given concrete research context. ID scholars have had a tendency to discuss ID in metaphorical terms, describing it as a process of learning "languages" and understanding different "cultures"; ID is a matter of "communication", "boundary-crossing", and so on. Arguably the lack of engagement with scientific practices confines these discussions to rather figurative talk. Our analysis of practices in the environmental sciences, however, shows that there are at present concrete methodological and more technical meanings to be given to "interdisciplinarity" in the form for instance of these modeling frameworks. Given the highly interdisciplinary and problem-oriented nature of the environmental sciences, we conjecture that our results are generalizable to some extent. In particular, we conjecture that similar ID methodological practices may be identified in other ID fields, and that the actual methodological structures we extracted in our case may be used as templates for structuring ID research elsewhere.

Secondly, while ID discussions have focused on the institutional constraints facing ID research in terms of discipline-centered reward systems and organizational structures (both giving individuals disincentives for ID research), our analysis above indicates how important cognitive constraints can be in shaping ID practices. While not all of these strategies could be used to handle any type of problem, none of these modeling strategies we have identified above are arbitrary with respect to cognitive constraints, but provide specific avenues for dealing with at least a subset of them. Modular model-coupling and substitutive model-coupling for instance are strategies which aim to build models collaboratively while preserving disciplinary modeling standards and methods. The prevalence of modular model-coupling in practice can certainly be explained by the difficulties of achieving integration when relatively heterogeneous theoretical frameworks are involved. At the same time, these choices mean that researchers often have to confront constraints that are not handled up front during the interaction process such as scale and other compatibility issues. Data-driven and integral modeling methods, on the other hand, avoid the difficulties of resolving methodological or theoretical conflicts by minimizing the required roles background disciplinary methods and theories play in model construction. As such they have some capacity to bypass scale issues or other issues of model incompatibility. In addition, reliance on little substantive disciplinary theory and method in the case of data-driven modeling opens the door for inclusive collaboration with, say, non-mathematical researchers, but potentially at a cost of excluding more theory-driven researchers. Reliance on a single integral modeling framework like SD has similar pros and cons. Analyses such as the one we provide here help show how cognitive constraints shape ID practices in concrete methodological terms.

Thirdly, these modeling frameworks can be understood as essentially *conservative* responses to the need amongst researchers and their funders for ID research. This conservativeness as mentioned at the start (in Sections 1 and 2) challenges the common expectation that ID problem-solving contexts will drive novel and transformative methodological and conceptual development. For the most part these frameworks either attempt to preserve methodological practices and conceptual frameworks by using established frameworks, or provide more neutral approaches which avoid substantive methodological or conceptual change and can be engaged in somewhat casually.

As a result, in the case of modeling in the environmental sciences, at least - if we factor out novel fields like ecological economics - we are seeing the *crystallization* of interdisciplinary practices around a limited set of conservative model building frameworks or strategies, instead of novelty and transformation. Hence, while ID studies promote a vision of interdisciplinarity as relatively fluid and inventive, the existence of this limited set of strategies, strongly weighted towards handling cognitive constraints in a conservative manner, points to the opposite. Normative expectations of what ID should be are not being met, even in an area like the environmental sciences, for which interdisciplinarity is increasingly accepted as good practice at an institutional level, and accordingly well-funded.

ID scholars may respond to this, as they often do, by declaring that many of the frameworks given above are not in fact cases of interdisciplinarity but instead cases of multidisciplinarity because such methods are not all truly integrative but represent more of an assembly of approaches which divide problems along disciplinary lines. For example, the model-coupling case may perhaps be considered just cases of "juxtaposing", "sequencing" or "coordinating", metaphors associated with multidisciplinarity. However as suggested above coupled models are not simply juxtaposed or coordinated, if we apply any straightforward meaning of those terms. ID work and agreement is required to build systems of models which work together effectively. Data-driven and integral approaches do combine variables and data from different fields into single models. Further, as MacLeod and Nagatsu (2016) point out, substitutive model-coupling arguably does result in a new product (a new modeling framework), and substantive levels of ongoing interaction which could not have emerged otherwise, such as using models from different fields to correct each other, even if this framework is built from very familiar model components and methods. Given these findings, we suggest that it is a better conceptual account-keeping to unpack the multi-dimensional notion of 'integration' in terms of actual methodological practices, than to insist that the notion be reserved for empirically unmotivated ideal notions of what interdisciplinarity is expected to be.

These conceptual issues aside, we think there are methodological rationales that drive crystallization, rather than transformation, in ID integrative modeling practices. These rationales are an extension of those applied in common disciplinary modeling

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[20] In contrast, in forestry MEY seems to be more accepted. In fact, Martin Faustmann, the first person who proposed the use of MEY as the management objective in 1894, was a forester.

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practices in the natural sciences and some model-based social sciences. Humphreys (2004, chapter 4), for instance, argues for the centrality of limited sets of what he calls *computational templates* within scientific fields and disciplines.[21] These templates are basic mathematical representational structures which are computationally tractable. One central aspect of disciplinary practice is the development and application of these templates, including the development of experimental methodologies and the production of data sets, etc., which can apply them, and mathematical investigation which can enrich the properties of these templates (sometimes called horizontal modeling). Such activities readily make sense from a cognitive perspective: restricting the methodology of a field to the development of a set of templates allows the development of standardized practices, and provides constraints which reduce the problem-solving choices researchers are confronted with.

Our idea of modeling framework is less concrete than Humphreys' notion of computational template. Frameworks, as we have described them here, exist at a more abstract level, prescribing *models of interaction* rather than the specific mathematical forms Humphreys has in mind. Nonetheless, given the complexity of ID problems in the environmental sciences and elsewhere, and the cognitive and institutional constraints scientists have to deal with, it is quite rational for them to pursue a similar kind of strategy with respect to ID research too, that is, a strategy which concentrates on the development of a finite set of modeling frameworks. Experiences from doing so can be collected, and methodologies developed to help standardize them and enrich them over time. Overall they have the ability to promote longer term collaborative or interdisciplinary methodological development, in a way that perhaps *ad hoc* ID interaction on a single problem cannot.

One of the putative strengths of substitutive model-coupling is in fact the degree to which it mirrors disciplinary practices and helps provide a foundation for solid collaborative methodological development and investigation. The cases we have observed combine pre-existing modeling frameworks, and at the same time move from relatively simple cases to more complex ones through step-by-step development, as in forest management models taking into account a non-clearcut regime (Tahvonen & Rämö, 2016), bioenergy and carbon storage (Pihlainen, Tahvonen, & Niinimäki, 2014; Tahvonen & Rautiainen, 2017), or reindeer management models taking into account government subsidies (Pekkarinen, Kumpula, & Tahvonen, 2015). Substitutive model-coupling offers a platform for building frameworks equivalent to something like Humphreys' templates, although templates devoted to collaborative interdisciplinary work rather than disciplinary work. Something similar is hoped with integral frameworks like systems dynamics. The original models produced in such frameworks over a longer term can be carefully scaled-up in complexity through back and forth interaction to consider more variables, and more complex relations.

This crystallization of practices of course serves to further crystallize at least for the present established disciplinary practices in ID work. The reliance on background practices and avoidance of methodological change is itself rationalizable on cognitive grounds given the domain specificity of practices and difficulties of overcoming cognitive and other constraints. But there is also another potential degree of mirroring here too. Just as it is reasonable to expect that innovation within disciplines occurs for the most part principally at the boundaries of disciplines, to prevent radical reformation (par Lakatos (1970) ideas of a protective belt), so it should be expected in ID contexts as well. That is, just as researchers commonly seek out modifications consistent with established methods and practices within disciplines,[22] researchers in interdisciplinary contexts are expected to do the same. In this respect ID practices recapitulate ordinary rational disciplinary practices.

This mirroring of disciplinary strategy has consequences not only for expectations about what ID looks like and what it can achieve, but also for the most effective ways to implement it. In particular, it raises a question about whether real-world problem contexts themselves are always appropriate contexts for ID work. If certain methodological platforms are seen as important poles of ID work in general, then there is arguably an interest in funding more theoretical research on these, such as research on model calibration for coupled-model systems. This methodological development is indeed already apparent in the environmental sciences themselves. Computational methods are being devised to help standardize and integrate models for coupling and calibration (Voinov & Cerco, 2010). Likewise, the typical 3-5 year funding schema seems out of step with the more cumulative nature of these practices, which, as within disciplines, require time to assemble and perfect. Additionally, the modeling frameworks identified above can represent sound and accepted strategies of ID integration for the purposes of making funding decisions. Funding applications are often promissory or vague about their plans for integration, leading to project results that do not meet any standard of integration. However choosing a well-accepted ID modeling strategy such as those above can help signal to funders both the seriousness of the intention to interact and a methodological pathway for doing so, enabling ID funding decisions which are much less speculative, or which resort to disciplinary criteria for sake of having no other. Further these modeling strategies require concrete sets of knowledge, techniques and skills to operate which can be used explicitly to train environmental scientists in interdisciplinary work.

To summarize, expectations of how ID can and should occur within the environmental sciences and elsewhere, we suggest, may not be well-aligned with a deeper understanding of how scientific practice operates, and in turn how ID can develop substantively and sustainably (i.e. continuously over the longer term). If this is true, then it does raise concerns about whether current ID scholarship has unrealistically high expectations about epistemic and practical gains from ID research. However, our study does not imply that we should simply lower expectations from ID research or drop it from science policy priorities. ID is recognized by practitioners themselves as a desirable goal, and some ID practices are yielding genuine gains. Nonetheless, both research policy and education science could do better by taking more account of the bottom-up systems scientists are themselves constructing to govern their ID interactions, and by helping advance those practices towards policy goals through sound educational practices and funding policies.

6. Conclusion

In this paper, we have identified four interdisciplinary modeling strategies in the environmental sciences, drawing on our past and ongoing case studies, as well as a review of the methodological literature in environmental sciences. We discussed the affordances

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[21] In philosophy of science concerning interdisciplinarity, Knuuttila and Loettgers (2014) use the term 'model templates.' Their focus is however on the general syntactic nature of these templates in facilitating ID transfer or exchange, where one template is applied in different discipline(s) than where it originated. ID in this sense is a very limited and special case that has been observed in history and philosophy of science (e.g. Grüne-Yanoff, 2016).

[22] Developments of modified models of choice in behavioral economics serve as perfect examples of this practice.

and limitations of each strategy, arguing that our typology provides a useful analytic framework to rationally reconstruct existing integrative ID modeling practices. Our typology is informed by practice, but at the same time motivated by our wish to provide theoretical-methodological insights to ID discussions by drawing on the philosophy of science. We have challenged the reliance of the dominant ID discourse on metaphors in analyzing ID practices, and criticized certain normative expectations in the ID Studies literature as out-of-step with actual ID modeling practices. The accumulation of substantial ID work and ultimately the crystallization of certain practices in the environmental sciences and elsewhere in the last decade offer an opportunity to develop more careful theoretical analysis of what ID is in practice, the constraints under which it operates, what can be expected of it now and in the future, and how policy can affect its future development.

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Appendix A. Supplementary data

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