Aims, Domains, and Models in Science

Abstract: There is a common view of modeling in the philosophical literature that ties modeling tightly to theorizing. In this paper, I demonstrate that conceptual models and modeling strategies widen the suite of aims associated with modeling such that modeling cannot be unified by practices of theorizing. Using conceptual models, I advocate for a view of modeling that takes seriously domain-specific goals and how they interface with modeling strategies such that modeling practices resist easy unification.

1. Introduction

Much of our understanding of models in science is owed to the analysis of a handful of models deployed in scientific practice taken to be exemplary: models like the Lotka-Volterra model of predator-prey dynamics from the work of Michael Weisberg (2006; 2007; 2013; Weisberg & Reisman 2008) and Jay Odenbaugh (2005; 2018; 2019)[1]; the Hardy-Weinberg model (a.k.a., equilibrium, law, or principle) in the works of philosophers like Elliott Sober (1993), William Wimsatt (2002), Christopher Stephens (2004), and Eugene Earnshaw (2015); Schelling's model used in the social sciences owing to work by Weisberg (2013), James Nguyen (2020), and Emily Sullivan (2022); and *C. elegans* or *D. melanogaster* in Rachel Ankeny's and Sabina Leonelli's work on model organisms (Ankeny 2001; Ankeny & Leonelli 2011; 2020). Each of these models is used in the service of developing general accounts of models and modeling practices in the sciences.

From the examination of some of the above exemplars, a common view of models has emerged. Namely, 21st century philosophical accounts of scientific models emphasize their representational capacities and their role in, or relationship to, theorizing. Commonly collocated in citations of the literature, Peter Godfrey-Smith (2006) and Weisberg (2007; 2013) appear as proponents of a particular kind of model-based theorizing and emphasize the representational capacity of models.[2] Weisberg argues that modeling constitutes a distinct kind of theorizing and, while Weisberg and Godfrey-Smith differ on their commitments about the nature of representation, they nonetheless deem representational capacities important for licensing

[1] See also, Levy & Currie 2015; Knuuttila & Loettgers 2017; Andersen 2018; Nguyen 2020.

[2] See, Levy & Currie 2015; Salis 2016; Irvine 2016; Downes 2021.

inferences about targets and for the proper assessment of models. Others, like Ankeny and Leonelli (2011) argue that what makes an organism a model organism is that it can be conceptualized as having a representational scope (the extent to which the results of a study of an organism can be projected out onto a target) and a representational target (a range of phenomena the organism is deemed to be the analogue of). In this sense, they suggest that model organisms can be thought of as mediators between theory and the world. On this view, an understanding of models is tethered to an understanding of theory and theorizing.

In this paper I will challenge the notion that models are solely theoretical entities and demonstrate that the model chosen as exemplary for our understanding of models influences the account of models that arises. I take this to offer a challenge to the idea that a unifying account of models is possible as models play a variety of roles in practice. To begin this challenge, I will explore an underrepresented model in the philosophical literature: the conceptual model.[3] More specifically, I will examine ecological conceptual models to produce an image of model-based science different from the more popular accounts in the literature that tie modeling tightly to theorizing. I argue that because a different picture emerges models should be thought of as tools that solve domain-specific problems, in line with that domain's diverse array of aims. This problematizes the ability to provide a general account of model-based science, tied to any one scientific aim or activity.

To this end, I first illustrate the development of conceptual models in the ecological domain (section 2) and then explain how they are evaluated drawing on an adequacy-for-purpose framework to do so (section 3). In section 4, I offer my argument for a domain-specific role for

[3] An exception is Alisa Bokulich's (2021) discussion of geological conceptual models.

models that troubles the idea of a unity of modeling practices. Then I offer some brief concluding remarks in section 5.

2. Conceptual Models in Ecology

Ecology has at least two overarching, interrelated aims. First, ecologists aim to reveal the dynamics at work in any given natural system by providing causal and theoretical understanding of them. Carefully crafted experiments and models are used in the generation of this kind of precise ecological knowledge. I take these to be theoretical aims from which explanations or predictions follow, assessed based on their, e.g., precision, generality, or accuracy.

For example, one team of ecologists, Stewart et al. (2004) aimed to explain the physio-chemical mechanisms and pathways at work in the San Francisco Bay that contributed to spinal deformities in splittail fish populations. To achieve their aims, they drew upon a diverse scientific toolkit, performing stable isotope tracer studies and gut content analyses to identify food webs, and constructed dynamic multi-pathway bioaccumulation models to simulate contaminant behavior. While Stewart et al. were primarily motivated by theoretical aims (to gain a precise causal understanding of some specified chemical contaminant), and so enlisted theoretical modeling strategies, their study illustrates the proximity to which ecological work finds itself to aims of risk assessment, ecosystem management, and policymaking.

A second overarching aim in ecology is the regulation and management of ecological systems. A team of ecologists, Gentile et al. concern themselves with these kinds of aims when investigating the degradation of The Florida Everglades. They describe the kind of theoretical ecological work performed above by Stewart et al., and the environmental regulatory strategies suggestive of it, as “command-and-control strategies that focus on single chemicals, in single media, and often affecting only one or at most, a few species” (Gentile et al. 2001, 232). Gentile et al. acknowledge that these kinds of command-and-control studies have contributed greatly to improved instances of ecosystem health but ultimately fail to contribute meaningfully to management. Gentile et al. explicitly call for “[r]egional- and landscape-scale assessments, involving cumulative risks from multiple stressors affecting a diversity of ecological resources” but acknowledge that these assessment styles “pose unique regulatory as well as scientific challenges” (ibid). Their aim is to alleviate some challenges like increased scale, scope, and complexity by offering a framework for tackling them. Their go-to tool in this effort is the *conceptual model*.

Briefly, what do conceptual models look like in ecology? The conceptual models under consideration here often take the form of box-arrow diagrams for various reasons. According to modelers, it is common for conceptual models to take this representational form because they are efficient tools for, “providing a compact, visual statement of a research problem that helps determine the questions to ask and the part of the system to study” (Jackson et al. 2000, 695). Gentile et al., add that “a conceptual model can engage the scientific community in an important dialog to articulate more clearly the individual perspectives of scientists” and offer a starting point “to scientists who have not previously focused on the environmental problem at hand” (Gentile et al. 2001, 235). The box-arrow diagram is the vehicle by which all of these aims are achieved. In this way, the model provides the basis for discussions, and “can also be a useful consensus building tool in collaborative research” (Jackson et al. 2000, 697). On the same vein, Gentile et al. stress that, “well designed graphics can immediately show scientists and decision-makers alike those facets of the system that are both important and highly uncertain, and how research resources should be prioritized" (2001, 235). In other words, the conceptual model provides modelers an arena from which to ask questions about the worthiness of investigation given the agreed-upon dynamics that the model represents.

Gentile et al.'s approach to management in the Everglades is to transform societal goals into conceptual models which will inform the ways in which scientists and policymakers pursue management of the ecosystem. Specifically, with an ever-growing human population, water reserves are continually shrinking and becoming more contaminated and degraded. The project Gentile et al. are interested in is the mitigation of further degradation and intervention strategies to improve the quality of the water reserves and the biosphere that is affected. As stated above, their approach is to widen the scale, scope, and complexity of the targets that they relate, and the best tool for this is a set of conceptual models. Explicitly, Gentile et al. indicate that conceptual models are good for goal setting, delineating the spatial and temporal boundaries of ecological systems, and the identification of stress regimes and ecological endpoints.

So, one use of a conceptual model is to organize data and knowledge, refine questions, identify hypotheses, and determine further ways to investigate the target through an iterative process of model refinement. However, the models are to remain simple, as not to obscure the ecological facts which would be good for generating hypotheses. The models are useful consensus-reaching tools, good for research teams to evaluate together in the furthering of their management aims. The models can even then inform what quantitative approaches are appropriate for further modeling. Jackson et. al. write, "[a] quantitative model is a set of mathematical expressions for which coefficients and data have been attached to the boxes and arrows of conceptual models," suggesting that a conceptual model is a good first step in determining what kind of mathematical approach to take next.

Christine Shoemaker doesn't use the term conceptual model explicitly but describes the move from this kind of box-arrow diagram (or conceptual model) to mathematical model as fundamental to the mathematical modeling process (1977, 76). Ecologists' own understanding of conceptual models is (at least some of the time) that they are a separate kind of model from quantitative models. Often, they describe conceptual models as a step in the direction toward quantitative modeling.

Another team of conceptual modelers, de Souza Machado et al. (2016), make explicit that one of the purposes behind constructing and proposing their conceptual model was the need for quantified studies of metal toxicity in aquatic systems. Their model follows the similar pattern described above: they reviewed a collection of diverse sets of data from published research to build and represent in box-arrow form an interconnected causal system of biogeochemical pathways responsible for metal contamination in aquatic settings. They conclude, "it is evident that the coupling of different models is mandatory to represent the estuarine environment as conceptualized here. Therefore, future models integrating quantitatively physical, biogeochemical and physiological processes occurring in estuaries are required for a realistic approach" (2016, 279). The conceptual model they propose is known by them to be insufficient for theoretical conclusions to be drawn. However, their model is introduced with the aim of providing bedrock for the construction of new more targeted models which they advise be coupled together to offer more robust explanations of metal toxicity.

Conceptual models of this kind act as an arena for scientists to organize data, come to consensus, and ask clarifying questions (Jackson et. al. 2000, 697). The iterative process eventually ends and questions about the usefulness of the model itself arise. The conceptual model is where researchers ask questions like "Will a quantitative model add to the study?" "Is there sufficient motivation to do the work?" "Will the time investment enhance the quality of the papers produced?" "Do the resources exist (mathematical or data) to answer the question?" (Jackson et al. 2000, 695). These questions suggest that, while the conceptual model is useful for organizing scientific data, it also serves to interrogate the scientific process itself. The model's utility is not only as an epistemic device, but as a device for the scientist to facilitate the process of good science.

Axel Gelfert nicely demonstrates that there are exploratory uses that models can be put to. For example, one use of models in an exploratory setting is as a starting point. Gelfert illustrates that in many cases of modeling there is no theory (or a lesser grasp of the underlying theory) to guide the investigation at the point in time which the exploratory model is being used. According to Gelfert, these are models of which, "questions concerning the model's truth or empirical adequacy would be premature" (Gelfert 2016, 84). Instead, starting point models are evaluated with regard to their exploratory aims and are considered one model in a succession of ever more complex models. Exploratory models are used in contexts such that "a constructive effort at model-building" (2016, 84) takes primacy over the integration of theory or observational data for exploratory models.

Further, Gelfert illustrates that a model may be exploratory when it is used for purposes of evaluating the suitability of the target. In many situations, scientists act in the absence of a suitable theoretic framework, so they engage in a sort of trial-and-error modeling strategy: scientists will identify the appropriate boundary conditions and engage in an iterative revisioning of the target as represented in the model. The scientists aim at "arriving at a stable 'research object'" (Gelfert 2016, 93). According to Gelfert, significant time is spent considering the laws that govern the target system, often as differential equations. The purpose of the exploratory suitability of the target model is to narrow the range of laws thought to be relevant within the proposed boundary conditions. So, using Gelfert's language, conceptual models as seen above are useful as tools to act as a starting point and to assess the suitability of a target.

3. The Evaluation of Conceptual Models

Wendy Parker introduces (2010; 2020) what she calls an adequacy-for-purpose evaluative view of scientific models which de-emphasizes the representational quality of models and highlights the purposes behind a model's use as the determinants of a model's success. This is not to say that models are never evaluated by their representational quality; adequacy-for-purpose suggests that a model is to be evaluated on its representational accuracy only when representational accuracy is an explicit purpose behind the model's construction and use.

Parker likens the adequacy of a model to hypothesis testing. Researchers using models can test how well the model fulfilled the purposes for which it was built and used. In some instances, the model can be tested directly by waiting to see if the purpose for which the model was built obtains. Importantly, the evaluation of models on this view prioritizes models in their contexts of use. Assessing a model's adequacy-for-purpose places the model, not in relation to a target, but to a problem space. That is, the model acts in relation to the user of the model, the target, the context, and the purposes for which the model was constructed.

Parker maintains that adequacy-for-purpose affords several benefits to model evaluation, not afforded by the representational account. First, models are not always used as good representations, but are used instead for practical aims. It seems only fair to evaluate a model that was designed for management aims on whether or not it facilitated the appropriate management protocols. Also, adequacy-for-purpose evaluation seems to work well for models that deliberately misrepresent their targets. Last, adequacy-for-purpose places the evaluative force onto the single use of a model, avoiding problems associated with broad claims about the representational capacity of a model generally. Parker highlights cases in which a model was deemed representationally accurate for some studies, but not for others. Adequacy-for-purpose notices variance in purposes over fixed contexts of use. In other words, that a model was successful once, does not mean it will be again if it's being used for different purposes. If all models are taken to be good as representations, then it becomes puzzling why a model may fail to be useful after it has been once already. According to Parker, "the adequacy-for-purpose evaluator will focus on aspects (and degrees of fit) that are considered most relevant for achieving the purpose of interest" (2020, 471).

There is no doubt that conceptual models are intended to relate to their targets. Suter offers a concise guide for the constructions of many kinds of conceptual models in contexts of environmental risk assessments. He says explicitly, "conceptual models are representations of the hypothesized means by which an activity or set of activities induce effects on ecological receptors" (Suter 1999, 376). Suter even stresses that the conceptual model sometimes attempt completeness, described as the inclusion of "all significant causal linkages" (394). Suter also finds merit in highly detailed, but managed conceptual models. He employs strategies of hierarchical and modular organization of system components in the model to find the balance between complexity and usefulness. The relation of the model to its target involves reasoning about the relevance of certain features of the target and including them in the model. However, this does not mean that a conceptual model is to be evaluated by its representational accuracy.

Suter provides a summary of the purposes and strategies behind the construction of conceptual models, offering three purposes that conceptual models serve in the context of environmental risk assessment:

A. "Their creation compels assessors to think through and clarify their assumptions."
B. They "serve as a communication tool for conveying those assumptions … In particular, the graphic version of the model should allow the audience for the assessment to understand what sources, endpoints, and processes are included and which are excluded."
C. And they "Provide the basis for organizing and conducting … the development of quantitative models … based on the conceptual model" (1999, 376).

Conceptual models are successful when they achieve these aims. The constructions of the different kinds of conceptual models all take stock of these purposes and strategies are deployed to maximize the fulfillment of these purposes. Suter outlines strategies he takes to be crucial for generating the three outcomes above:

> "(1) Make the models explicitly mechanistic. (2) Define the compartments as functional groups. (3) Include the exposure-response relationships. (4) Create hierarchies of detail so that all important processes can be included without creating massive and confusing charts. (5) Create modular components of the model representing the activities to be assessed, influences on the endpoint receptors, and site-specific entities and processes that link activities and receptors." (Suter 1999, 376).

The aims here are associated more closely with communicability and collaboration than of representational accuracy.

As Parker outlines, adequacy-for-purpose "models are not just representations but also tools that are selected and used for particular epistemic and practical purposes" (Parker 2020, 459). Suter is reasoning about how best to achieve certain epistemic (e.g. clarifying assumptions) and practical (e.g. communication) aims and his modelling strategy internalizes these aims. Also, Suter's reasoning behind the construction and use of conceptual models fits well in Parker's adequacy-for-purpose evaluative schema. Specifically, it fits with her concept of $\text{ADEQUACY}_{\text{C}}$:

> A conceptual model employing the strategies i is adequate-for-purpose if and only if in instances of environmental risk assessments (C) the use of conceptual models with features (1)-(5) (M), purposes A–C are very likely to be achieved.

Suter's guide is an exercise in indirect adequacy-for-purpose testing. The guide is designed to showcase the kinds of strategies that work well to achieve the kinds of aims that conceptual modelers have. In this case, it is backward-facing, acknowledging the past conceptual modeling strategies that have worked to fulfill the aims of clarifying assumptions, communicative aims, and providing the basis for quantitative approaches.

To sum up, conceptual models are evaluated by how well they allow for an exploration of a problem space that includes users, methods, goals, and the model itself in the evaluation. Conceptual models—both the construction process and the completed model—facilitate the interrogation of epistemic and practical aims as well as work to achieve them. Suter applauds the deployment of these strategies to conclude his guide: "[e]ffort devoted to development of the conceptual model for an ecological risk assessment is amply repaid during the risk analysis, characterization, management, and communication processes" (Suter 1999, 395). These aims that guide conceptual model construction depart from the kinds of aims typically associated with theoretical models, like an emphasis on representational accuracy.

4. Models as Domain-Dependent Tools

In philosophical accounts of scientific modeling, it is not uncommon to see some mention of the high degree of attention that has been paid to quantitative models. This is mostly unsurprising given the proportion of quantitative models now being used in nearly all fields of science (Downes 2021, 37-39). Some of the discourse has been spent deciding how mathematical models can possibly represent and offer theoretical explanations of real-world targets (e.g., Morrison 2015). Prima facie, it seems puzzling to say that a mathematical equation represents or resembles a target in the world; after all, they're just a bunch of equations that look nothing like their targets! Nonetheless, it is from an assumption that models do in fact represent and from close examination of quantitative models that much of our philosophical understanding of the function of scientific models has emerged. A models-as-representations view has influenced how many describe what models are, what they are used for, and what accounts for their successful deployment. Thus, for many, to understand models is to understand how they represent.

Further, philosophers have asked about the relationship between models and scientific theories. The semantic view of scientific theories designates formal set-theoretic structures—models—to provide the truth conditions of theoretical sentences (Suppe 1977; van Fraassen 1980). Per the semantic view, all scientific theories are tied to models of this kind through isomorphic relationships. However, the semantic view of theories has been criticized as being too distant from the actual ways in which scientists use and create models in practice (see, e.g., Downes 1992). For this reason, others have moved on from this semantic approach. Nonetheless, models (and their construction and deployment) are seen as clinging closely to theories and theorizing. What emerges is a common view of scientific models as theoretical, to be assessed based on their representational quality (however representation is interpreted).

My illustration of conceptual models and modeling practices in ecology demonstrates that modeling practices contain a swathe of aims (both epistemic and non-epistemic), evaluative criteria, purposes, and uses that should broaden the available answers to questions like, “what are models good for?” and “when is a model a good model?” What emerges from my analysis is an account of models that contains the following features:

- Models organize current knowledge.
- Models simplify a problem space.
- Models facilitate hypothesis generation and exploration.
- Models are tools for communication and collaboration.
- Models are educational and pedagogical tools.

In what follows I elaborate on these features.

Conceptual models provide a framework for organizing ecological knowledge by identifying and representing key variables, processes, and relationships within a target system. Conceptual models can also inspire the development of new hypotheses by highlighting the causal mechanisms and patterns within ecological systems. Ecologists use these models to propose explanations for observed patterns or to explore potential scenarios and their consequences. Moreover, conceptual models are often the first step in the construction of more formal or mathematical models. They exist as starting points for the theoretical models that often follow. In this sense we may think of them as exploratory.

Ecological systems are often complex and challenging to study directly, especially when the management of one or a handful of stressors in the system is the goal. Conceptual models allow researchers to simplify and abstract these systems, so that they can focus on the most relevant factors and interactions while ignoring less significant details. This simplification enables ecologists to gain a better understanding of the underlying processes and mechanisms driving ecological phenomena.

Building off of the last point, conceptual models provide a common language and framework for communication and collaboration among ecologists. By using standardized depictions, such as diagrams and flowcharts, ecologists can convey their ideas, theories, and findings more effectively to wide audiences, including non-experts. Conceptual models facilitate the exchange of knowledge, promote interdisciplinary collaboration, and are developed to encourage the comparison and integration of different ecological theoretical frameworks and perspectives. The construction of conceptual models as a collaborative exercise also explicitly interrogates stakeholder values as a legitimate determinant of the relevant variables to be included in the models and subsequent management policies based on them. Additionally, conceptual models are evaluated based on the success of these collaborative aims.

Last, conceptual models are valuable for teaching and learning ecology. They help learners grasp complex ecological concepts and theories, visualize abstract ideas, and develop a deeper understanding of ecological systems. Conceptual models can (and to Jackson et al., should) be used in dissertations, textbooks, lectures, and educational materials to convey ecological principles and demonstrate how different factors interact within ecosystems. The model’s ability to incorporate current ecological knowledge and simplify a problem space lends well to this feature.

Conceptual modeling need not be tied to theorizing, and thus, all models need not be theoretical models. I take theorizing, and thus theoretic modeling, to be an activity oriented towards providing products like explanations and making predictions, beholden to certain epistemic aims—aims like accuracy, precision, and generality—for which representational quality is important. Conceptual modeling practices show fidelity to a wider class of epistemic values, including effective communication and hypothesis generation and conceptual modeling is deemed successful when a research project's worth is determined, or when management strategies are considered and weighed and are consistent with values held by stakeholders. Conceptual modeling offers scientists a tool to interrogate the scientific process itself and think about values as they directly bear on scientific work.

Conceptual models are not theoretical models as this is not their purpose, nor are they thought to be good for theorizing by those who deploy them. We should expect the role and function of models to reflect the purposes to which they are put, tailored to the aims of the domains in which they are developed. Models are used in all sorts of problem-solving contexts, including non-theorizing contexts like risk assessment and management.

5. Conclusion

A look at scientific practice reveals a suite of diverse modeling practices. Conceptual modeling in ecology is just one such unique practice. As seen, conceptual modeling contains a diverse array of aims and goals, from which we can reconstruct an account of modeling that suits those aims and goals. The selection of any exemplary model will reveal a similar set of domain-specific modeling practices, tailored to that domain's aims. From this, I advocate for a view of models that ties them to the problems and aims of specific domains; wherein modeling practices in one domain will not be easily translatable to another domain and no one-size-fits-all account will easily capture all modeling strategies. I have argued that popular characterizations of model-based science—as one strategy of theorizing with an emphasis on representational accuracy—have failed to account for these diverse modeling strategies and characterized model-based science as more monistic than is justifiable, based on the initial selection of exemplars. Based on my selection of conceptual models, this becomes apparent.

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