Environmental Modelling & Software 55 (2014) 70–76

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Strategies for communicating systems models

Damon M. Hall [a,*], Eli D. Lazarus [b], Todd M. Swannack [c]

[a] Center for Sustainability, Saint Louis University, Des Peres Hall, Suite 203E, 3694 West Pine Mall, Saint Louis, MO 63108, USA
[b] Environmental Dynamics Lab, School of Earth & Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff, CF 10 3AT, UK
[c] US Army Engineer Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180, USA

ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form
20 December 2013
Accepted 2 January 2014
Available online

Keywords:
Communication
Cultural models
Mental models
Policy
Stakeholders
Sustainability science

ABSTRACT

Sustainable environmental policies are rooted in knowledge and assumptions that decision-making authorities hold regarding specific social–ecological settings. These decision makers are increasingly informed by systems models. Diverse audiences for environmental science and sustainability policies magnify the importance of clear model communication. This essay offers a summary of best communication practices for situations in which bridging modelers' and non-modelers' conceptions of a given system—their respective mental models—is a principal challenge. Synthesizing social research from technical communication, educational psychology, and science communication disciplines, we discuss common areas of confusion in comprehending and explaining complex information, and present strategies model developers can use to ensure their model presentations are understandable and meaningful to audiences. We argue that accessible and socially adoptable explanations benefit from modelers listening to target audiences and anticipating how and why audiences may fail to understand aspects of a model.

1. Introduction: communicating models

Interdisciplinary methodologies in the sciences are a response to overwhelming evidence that human activities are a dominant force of change in natural environments (Crutzen and Stoermer, 2000; Haff, 2003; Holling et al., 1998; Hooke, 1994, 2000; Ostrom, 2007; Vitousek et al., 1997). Where environmental science and policy converge, how do interdisciplinary teams of researchers, natural resource managers, and practitioners integrate diverse kinds of expertise into meaningful representations of human–environment systems useful for decision-making? To disentangle the processes connecting research science and actionable policy—the Gordian Knot ubiquitous in post–normal sciences such as sustainability science and decentralized environmental governance—working groups are increasingly incorporating lay characterizations of resource systems into models of human–environment dynamics (Cash et al., 2006; Clark, 2007; Kates, 2011; Kates et al., 2001; Pohl, 2011; Schmolke et al., 2010; Talwar et al., 2011). Combining scientific and lay knowledge into an accessible (and politically acceptable) system representation, which then becomes a tool for deliberating about environmental problems and making decisions, both recognizes the benefits of public-engagement practices for improved governance (Innes, 1998; Manor, 1999) and heightens the importance of clear, careful, and strategic communication regarding model definition, development, and explanation.

Public participation in environmental planning brings diverse audiences in contact with policy making, science, and models, elevating the importance and consequence of modeling conversations. It is inevitable that the act of communicating the rationale, concept, results, implications, and limitations of a model influences *how* the model is used and perceived: the "variance in the *quality of model communication* between model developers and decision makers contributes to the wide variance in attitudes towards models" (Glaser and Bridges, 2007: 442, emphasis original). Where models represent integrated interdisciplinary science (Grant, 1998; Heemskerk et al., 2003; van der Leeuw, 2004), modelers are ambassadors for both the model and the underlying science as an appropriate method of representing a given system. In this Information Age where the credentialed "scientist" and "technical expert" are not granted indiscriminant public trust, communicating science well to community planners and stakeholders is paramount (Mooney and Kirshenbaum, 2009; Nisbet and Mooney, 2007; Sarewitz, 2004).

Perhaps the best-known, worst-understood models are those of climate science (CCSP, 2009; Fischhoff, 2011; Fyfe et al., 2013; Nisbet, 2009). Pidgeon and Fischhoff (2011) note that public

* Corresponding author. Tel.: +1 314 977 4154.
E-mail addresses: damon.hall1@gmail.com, dmhall@slu.edu (D.M. Hall), LazarusED@cardiff.ac.uk (E.D. Lazarus), todd.m.swannack@usace.army.mil (T. M. Swannack).

1364-8152/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2014.01.007

understanding of climate change is impaired in part because the science of climate change relies on simulation models that have often been communicated poorly. The contentious public debate surrounding anthropogenic climate change, with entrenched adherents and opponents, illustrates how model-generated predictions can have huge and potentially divisive social, economic, and political impacts (Begley, 2007; CCSP, 2009; Fischhoff, 2011; Nisbet, 2009). Because an accepted system representation effectively denies alternative representations, model conceptions can establish—and decommission—entire paradigms of resource management practices, enacting lasting changes in economic, social, cultural, and ecological functioning; such models become perceived in terms of how they affect budget priorities, project approval, and policies (Jacobson and Berkley, 2011; Latour, 2004). Irrespective of the model developers' intentions as tools for decision making, models are political, set within a backdrop of political gains and losses (Allen et al., 2005; Barnaud et al., 2012). Such potential political ramifications of a model further complicate its communication.

Even if a given model is relatively "simple," models are an inherently complicated concept because the term 'model' itself is ambiguous, meaning different things to different people. The more diverse an audience is, the more daunting it becomes for model designers to communicate the kind of tool their model is and what it does.

Unfortunately, modeling textbooks lead students into the experience of modeling but omit practical aspects of communicating models. While advice for writing model descriptions (Aber, 1997; Peck, 2000, 2004) and participatory model building (Metcalf et al., 2010; Thompson et al., 2010; van den Belt, 2004) are helpful resources, the challenge of designing a modeling presentation for a non-technical citizen and decision-making audience is often left to experiential learning.

In this essay, we present strategies that model developers can use to ensure model presentations are accessible and meaningful to target audiences of non-modelers. Specifically, we focus on strategies for communicating models with decision-making authorities and public audiences during stages of model development, analysis, and application. If the ultimate success or failure of a human–environmental model used in decision-making stems from the degree of stakeholder involvement in the modeling process (cf. Schmolke et al., 2010), then sensitivity to users' understanding of systems and situational context is fundamental to building and communicating a model that stakeholders and decision-makers are inclined to adopt. Whether involved in participatory, descriptive, or predictive modeling, modelers can apply the strategies we offer to communicate models of all types. First, we discuss the role of models as tools in decision making and explore aspects of communicating with diverse audiences that modelers should understand. Then we present three general obstacles to communication typical of complicated topics, and suggest ways to overcome these challenges in modeling presentations.

2. As many definitions as people in the room

At a recent workshop for a U.S. National Park Service project, approximately 30 experts in natural resource management and socio-economics met to develop a conceptual model of park visitation (Swannack et al., 2009a): why do people visit parks? what does visitation reveal about visitor preferences and expectations? and how does visitation affect attributes of the park, such as its accessibility and the quality of its physical condition, over time?

The conveners explained that the objective of the workshop was to create collaboratively a description of park visitation as a system. By identifying factors and processes related to visitation, the resulting model would help decision-makers understand which park attributes and visitor preferences should be monitored to ensure the relevance of park management programs. The conveners discussed the typology of systems models (cf. Meadows, 2008), defined the kind of model they envisioned, and presented examples of representational models they considered illustrative. Despite the participants' expressed familiarity with modeling, confusion arose among the participants and between the participants and the conveners over different interpretations of the term "model". Participants familiar with predictive modeling thought the objective of the workshop was to create a data-driven, predictive model, one that would use past visitation trends to predict future visitation trends.

Consequently, much of the workshop was devoted to discussing essential differences among various model types and analytical methods known to the audience in terms of the workshop's intended model. This example highlights an important lesson about communicating models: even for an audience of technical specialists, the model type, a justification for its selection relative to other modeling approaches, and the objectives for its application to the problem at hand should be explained clearly in terms of the audience's pre-existing experience with modeling. Because different disciplines and professions construct different kinds of models, when speaking across disciplinary lines modelers tend to communicate poorly about implicit assumptions their models use (Harte, 2002; Jakeman et al., 2006; Schmolke et al., 2010). So what is a given model for? What output does it produce and from what input? How should its results be interpreted?

3. Models as tools for explanation or prediction

Fundamentally, a model is a tool for insight. Models help investigators examine and refine hypotheses, typically in combination or in coordination with other kinds of empirical methods. Although a transdisciplinary model typology is beyond the scope of this paper, summaries of technical and conceptual challenges associated with particular modeling types and techniques are available for simulation modeling (Sokolowski and Banks, 2011), stakeholder contexts (Voinov and Bousquet, 2010), social and geospatial agent-based modeling (Crooks et al., 2008; Gilbert, 2008), and systems modeling (Meadows, 2008), among other subsets. More generally, however, in terms of purpose, models tend to fall into one of two categories (cf. Haff, 2003; Murray, 2003, 2007). A model may be designed as a description, whether quantitative or qualitative, that offers an **explanation** of the dynamics of a phenomenon or system. The model may present a big-picture, simplified, or abstracted perspective that makes a system more tractable for problem formulation, hypothesis testing, or management (Allen et al., 2005; Grant and Swannack, 2008). Alternatively, a model may be a tool for **prediction**, such as a statistical model used to forecast trends or a detailed simulation model that provides investigators with specific information about what a system will do in the future under a given set of conditions (Glaser and Bridges, 2007). A model may be an interesting idea unto itself and may be a key that unlocks new answers, but a model is ultimately a means rather than an end.

The importance of clarifying a model's purpose, from its underlying research question to its analytical limitations, cannot be overstated. Returning to the National Park Service workshop example, the conveners and the participants had in mind two different purposes, which led to confusion concerning the model the workshop would yield. Participants thought the model's purpose was to predict visitation. Such a model might include demographic data, attendance records, and visitor feedback about infrastructure (e.g. parking availability, facilities, natural amenities). Regression analysis might then organize those variables into a hierarchy of relative importance, which practitioners could then apply to anticipate future attendance. The Park Service hosts conceived an explanatory model addressing the sum of interrelated park attributes, conditions, and circumstances explaining why people visit national parks. The aim was to develop this explanatory model leveraging the practitioners' expertise to capture relevant attributes and desired features motivating visitor attendance. The model would reveal aspects of the national-park experience practitioners could monitor in concert with visitation records and ongoing ecological monitoring.

Although the purpose of the desired model was different than many of the model participants' expectations, both an explanatory and predictive model would eventually be used to inform visitation research and management. Even with the same end goal, why did the workshop conveners and participants find themselves at crossed purposes? One reason may be that those who came to the workshop arrived with a model of one kind or another already in mind—in this case, a model of what constitutes a model.

4. Connecting with audiences' mental models

For a given system, people intuitively construct a practical understanding of how the system works and how to work within it, often without explicit analysis or even words (Meadows, 2008; Westervelt and Cohen, 2012). This understanding of the system is built from years of first-hand experience and observations made from within the system. Tacit lay conceptualizations of ecological functioning, for example, are passed down through social learning, business practices, and woven into cultural fabrics of everyday living like farming, ranching, irrigating, fishing, hunting, and others (Costanza et al., 1993). Although intuitive models are common to daily cognitive functioning, people often struggle to articulate these implicit understandings. Such mental models are often expressed piecemeal in ordinary conversation, story, shared memories, normative values, and common social meanings (Jones et al., 2011). These mental schemas condition how individuals and societies interact with their environment (Butzer and Endfield, 2012).

Because viable, actionable policy necessarily involves localized cultural factors (Hall et al., 2012a), getting an environmental-management model "right" is a matter of creating a meaningful representation of the system that is useful for adapting human practices. Contradictory as the idea may sound, a meaningful model is one that accounts both for empirical data and for what local citizens consider true about the system of which they are a part.

Therefore, the difficulty of building and explaining models to decision makers and stakeholders lies in the diversity of perspectives that have legitimate claims of knowledge about the system of interest. Any model developed by an expert "outsider" will encounter resident experts' "insider" mental models. Communicating models requires anticipating and addressing the key components of the audiences' cultural models (shared mental models) and employing the vernacular vocabularies used locally to discuss the system (Abel, 2003; Paolisso, 2002; Paolisso and Dery, 2010). Ideally, model developers formulate model objectives with the participation of model users (Schmolke et al., 2010; Voinov and Bousquet, 2010). Because audiences pay close attention to what will directly affect them, they should be able to clearly see their interests, lived observations, familiar landmarks, and the key decisions required of them somehow reflected, represented, or signified in the model (Peterson et al., 2004). Using the commonly-used local terminologies, place names, and vocabularies when presenting a model not only helps assure audiences that their interests are included in planning conversations, but also helps people mentally move from personal interests to conceptual abstractions of the system as a whole (van den Belt, 2004). Conversely, in cases where participants' values and policy preferences lead them to believe in different models, it may be necessary to provide a more abstract account of the system (see Barnaud et al., 2012).

Good communicators, whether about models or otherwise, are audience-centered: they attain an understanding of audiences before developing presentation materials. This involves acknowledging and investigating the diverse ways in which their audience may "know about" something, and therefore the variety of mental and cultural models shaped by experience that audience members carry with them. Such a sense of the audience requires some direct or indirect social research, which can be informal or formal (cf. Hall et al., 2012a; Paolisso, 2002). This research might involve speaking with members of the targeted audiences or speaking with someone who has knowledge of the audience. An audience analysis (see Box 1) can help a modeler understand the cultural context of a problem; the result is better preparedness, the goodwill of the audience for acknowledgment of their expertise, and often a model of greater utility.

BOX 1
Audience-analysis questions to improve model communication

1. Who are the decision makers and stakeholders?
2. What are their interests, desires, and motivations for participating in planning?
3. How do audience members understand the system of interest?
   - How do they interact with or experience the system?
   - What features of the system do they pay attention to the most?
   - How do they monitor or observe the system?
   - How do practitioners make sense of changing conditions?
   - What local vocabularies of terms, images, and concepts do they use to explain various system aspects and characterize problems within the system?
4. What other driving factors, significant events, and past conflicts within the decision-making context should be considered?
5. What prior experiences have audiences had with models?

5. Mental and cultural models shape environmental management

For a given human–environmental system, understanding the spectrum of interests, motivations, and intuitive knowledge embodied in audiences establishes a foundation for communicating a model in a manner that both appeals to the interests of various audiences and draws out conflicting assumptions or conceptual obstacles in their existing cultural models. Whether they are elected public servants, policy makers, trained natural resource managers, entrepreneurs, landowners, or citizens, audiences who participate in environmental planning tend to identify with, and are informed by, specific parts of their environmental system. For example, on a large river like the Yellowstone (Montana, USA), landowners who live and/or work on a particular reach of the river are most interested in activities and rule changes happening upstream that affect their quality of life (Gilbertz et al., 2011). In this way, resource users' interests typically follow the pattern of the resource itself and their beliefs about what affects it (cf. Ostrom and Gardner, 1993; Peterson et al., 2004). By contrast, decision-makers in official, authoritative capacities may be less likely to identify with a specific geographic location than with a jurisdiction, region, or metric of system health, thus operating from cultural models that in part account for duties of the office, organizational mission, and the budgetary and legal responsibilities of their position within the organization. Decision-makers need to be able to readily identify the key aspects of the system that hinge on their management choices, including the full cascade of system components that a decision one way or another will affect, especially when a model is part of a formal deliberation process (Glaser and Bridges, 2007).

From a consumer's choice, to a farmer's operations, to an industry's practice, to a policy agreed upon by legislators; the norms, rules, and logics of an environmental-management action are built upon on a body of generalizations about what is true in a particular setting. Environmental policies are built upon a baseline of assumptions about the social-ecological system. An effective model can clarify and improve communication about what those generalizations and key system assumptions are (Forrester, 1994; Krebs, 2000) by serving as a common language across often divisive discipline and sector boundaries (Harte, 2002; Jakeman et al., 2006; Schmolke et al., 2010; van der Leeuw, 2004), and across the working cultural models to which people are inclined to hold tight (Jones et al., 2011).

6. Three obstacles in communicating models

An accessible technical explanation of a model can benefit from anticipating how and why audiences may fail to understand aspects of the model. Synthesizing social research from technical communication, educational psychology, science communication, and instructional design, communication scholar Katherine Rowan (1992, 1995) describes three common areas of confusion audiences have in comprehending complex information. We recast those common technical-communication obstacles in terms of modeling communication, with examples of audience analysis useful for identifying likely obstacles and designing presentations that address common communication challenges before they arise. Although we know of no pre-established formulas for presenting models that guarantee success, literature suggests there are more common communication breakdowns when communicating technical subjects like models.

6.1. Obstacle 1: confusion regarding a concept

Communication involves negotiating shared meanings (Richards, 1936). One area of misunderstanding involves the meaning of a key term or concept. Many key terms have unique meanings among different social groups; meanings differ by trade, academic discipline, or geographic locale. When modelers and planners wish to use a specific technical term, one way to determine how audiences will interpret the term is to simply ask them during the audience analysis.

For an unfamiliar key concept or term, linguistics and science education research show people have difficulty distinguishing a concept's **essential features**—elements that are always present—from its **associated features**, elements that are typically coincident but not necessarily so (Rowan, 1995). An elucidating explanation, which helps audiences understand a key term with an unfamiliar meaning, emphasizes this distinction between essential and associated features. The elucidating explanation (a) uses an exemplar of the concept that (b) lists the concept's essential features, (c) provides a variety of examples and non-examples, and (d) gives the audience opportunities to practice discerning the difference by looking for the essential features that differentiate examples from non-examples (Tennyson and Cocchiarella, 1986). For example, during the research phase of a comprehensive water-management model for the Yellowstone River (Montana, USA), the U.S. Army Corps of Engineers wanted to organize the model's presentation around the technical concept of a "riparian corridor" (Gilbertz et al., 2007). Researchers asked audiences what they understood about this term to determine the utility of the concept as a point of departure for further discussion (Hall et al., 2012a). The feedback offered very specific material for an audience-specific elucidating explanation (see Box 2).

BOX 2
Elucidating explanation of 'riparian corridor' (Obstacle 1)

> A riparian corridor is the space where the river occupies and influences throughout all of its stages of high and low water. It is a space determined by natural forces; so it is on both public and private lands. Locally it has been called the "meander-land" and "where the plants and wildlife are." It is not the transportation, medical, or energy corridors, because it is a naturally made space. But like these manmade corridors, the riparian corridor is a continuous connected pathway of water and life. It is important to note that just because this space is designated as a management priority does not mean that the government is going to take this land from owners or prohibit all activities within the riparian corridor. The term is mostly useful to re-conceptualize how the many responsible agencies can maintain the health of this place which in turn maintains the quality of water for the many uses dependent upon the corridor like irrigation, wildlife, fishing, drinking water, and water for regional businesses.

6.2. Obstacle 2: difficulty picturing the overall system

Another reason an audience may misunderstand technical information stems from the difficulty of forming a mental picture of a complicated system. Education psychologists and systems theorists argue that people have trouble envisioning systems with many variables, feedback loops, and extended time frames (Forrester, 1969; Mayer and Anderson, 1992; van den Belt, 2004). A model can provide a logical, visual representation of a system and the research question it frames (Grant, 1998), but audiences often end up confused because modelers inadvertently obscure the concept by explaining too many details (Grant and Swannack, 2008).

For audiences to develop a useful picture of the overall system, model communicators need to help audiences (a) form a general impression of the system so that they (b) may grasp the system's component parts and connective processes (Rowan, 1995). First, modelers can develop a summary image (D'Arcy, 1998) or firstorder description that identifies the critical components, processes, and outputs of the system (van den Belt, 2004). As with a sketch, the aim is to capture the structure and general impression of the system. Effective strategies for verbally explaining the model include (a) structure-suggesting titles such as "Spaceship Earth" or "Five Areas of Study" and (b) organizing analogies such as "your brain works like a computer" or "a wetland is like a filter" (Rowan, 1995: 245), although studies show that the best explanations stay with one analogy rather than mixing different analogies (Rowan, 1992).

Images and visual aids allow all parts of a system to be displayed at once, but the fundamentally sequential nature of writing and speaking forces a linear structure of explanation that is functionally different than systems (Meadows, 2008). Therefore, good explanations of system properties have (a) easily discernible points and (b) clear connections among them that create a lucid narrative form (see Allen et al., 2005; Booth Sweeney, 2008). Effective verbal and written explanations of systems are easier to comprehend when they use clear headings, topic sentences, signaling phrases (e.g. "the main point is…"), and transitions that emphasize the relationships among components (Rowan, 1992).

One approach to stepping an audience through a model is to present a sequence of slides in which the model's construction is depicted with simple shapes, and each step is paired with details and real examples that ground the conceptual form of the system in ways familiar to the audience (see Box 3). Color-coding the model depiction can help audience members recognize parts of the system summary that speak to their expertise and how the model represents ways in which their knowledge is linked to other system components.

Describing how the model came together, what motivated its design, successes and failures in its development, choices among alternative interpretations, and encounters with common misconceptions can lend the modeling process more transparency for the audience—but at the risk of overloading them with extraneous detail. Because there is always more to tell, a clear presentation is a function of careful editing. Complicated numerical analyses are less compelling, and harder to absorb quickly, than the comparative general trends that arise from those complicated numerical analyses; guiding the discussion so that it periodically resets to the big-picture, system-scale view will also emphasize critical connections and implications within the system of special significance to resource managers and decision making (Glaser and Bridges, 2007; Grant and Swannack, 2008).

Defining the boundary between what a model does and does *not* do is an important part of helping audiences build their understanding of a model's concept and capacity, and comes back to whether the model's purpose stems from explanation or prediction. Moreover, the level of detail required to address the limitations of a given model is audience dependent. Is the audience a select group of experts making decisions on the basis of predictions framed within some window of accuracy? If so, then perhaps they already share a strong, mutual understanding of the concept at hand. If not, and the audience is diverse or the group, despite its selectivity, does not share a mutual conceptual framework, then even a predictive model must first be explanatory. Explaining the limitations of a model is irrelevant if audiences do not grasp both the model's conceptual underpinning and what the model itself represents. Understanding the model's fundamentals can only make audiences more discerning about the model as a tool; audience analysis should help the modeler learn what audiences expect the tool to do.

BOX 3
Depicting the overall system (Obstacle 2)

> In a talk to a targeted audience of researchers from a mix of disciplines, modelers presented a conceptual depiction of specific research questions through which experts from various fields could connect. Several months of conceptual modeling yielded a visually sophisticated depiction of the research too challenging for audiences to interpret easily. Modelers developed a revised presentation that began by describing each disciplinary role in the project as a discernible part, assigning those roles a designated color, shape, and spatial position on the presentation slides. As the conceptual model came together, audiences from specific disciplines were able to locate and track "their" role in the larger system.

6.3. *Obstacle 3: conflicts with pre-existing cultural models*

People spend lifetimes building intuitive understandings of how the world works. When a model clashes with audience members' beliefs, logics, or values, the dissonance disrupts their receptivity to the model's assumptions. To overcome this obstacle of conflicting representations of reality, Rowan (1992, 1995) suggests organizing talks with a **transformative explanation** that acknowledges the audiences' pre-existing notions of the system and transforms it with an alternative explanation. A transformative explanation (a) either states the existing "lay" or "implicit" description of the system, or asks questions to elicit one, and (b) discusses its plausibility, perhaps by including supporting observations. The modeler then (c) points out, using examples familiar to the audience, where the existing description falls short, (d) presents the alternative explanation, and (e) demonstrates how it more effectively represents the system (Rowan, 1995: 246).

Effective transformative explanations neither dismiss nor discredit lay cultural models. Rather, they help audiences break with parochial perspectives about the natural world by using the audiences' relevant observations to establish an alternative perspective for interpreting, managing, and treating familiar places (see Box 4). "Thinking in dynamic systems starts with examining the readily available beliefs we hold, followed by a willingness to break with habitual thought patterns and examine new alternatives" (van den Belt, 2004: 23). Few are easily persuaded to part ways with their implicit theories (Jones et al., 2011); educational research shows that the chief difficulty in this kind of communication is getting an audience to see why their existing understanding of a given concept may be inadequate, and why another view is perhaps more valid (Rowan, 1995).

Breaking with or complicating existing beliefs is not always a matter of a knowledge deficit. Research on cultural cognition suggests that audiences filter their views on science in a manner that maintains consistency both with cultural values and with the values of trusted persons (Kahan and Braman, 2006). Particularly in the context of polarized political issues, cultural commitments tend to precede factual beliefs (Kahan and Braman, 2006). An audience might understand the implications of a model perfectly well *and* have various reasons for maintaining lay assumptions. Audiences may therefore struggle to navigate or control the interpretive frameworks typical of land use management and planning (Hall et al., 2013). Information that threatens cultural commitments is easily dismissed. Effective transformative explanations affirm cultural values. Yet again, analyzing the audience can aid understanding their cultural priors.

BOX 4
Transformative explanation (Obstacle 3)

For years, conservation managers of a population of an endangered amphibian relied on data from a single study site. This resulted in a management perspective that lacked the dynamics of dispersal necessary to understand the population's persistence. Modelers synthesized related research from more recent field studies to develop a spatially explicit, agent-based model to understand dispersal patterns at a landscape scale and how those patterns might respond to various environmental conditions. The model incorporated the study already familiar to the audience of managers, offering an explanation that affirmed managers' existing mental models of the system. The model also transformed prior understandings by showing the insights gained from a larger spatial domain. Modelers were able to point out how a model accounting for dispersal dynamics more closely mimicked the natural system than original implicit models. Equipped with a more complete picture, managers re-prioritized conservation efforts.

7. Conclusion: communicating model results

Meaningful systems models might not bring the perspectives of decision makers, communities, and practitioners into agreement, but may bring a cacophony of mental and cultural models into alignment. As tools for integrating information, systems models lend shape to interactions among scientists, citizens, and policy makers that guide decisions and actions. Where models expose or overturn tacit assumptions previously integral to decision-making processes, how decision makers understand the implications of their prior assumptions can have lasting impacts on integrated economic, social, cultural, and ecological systems. Although a lack of information about ecological functioning can contribute to poor environmental policy decisions, the provision of this information alone is not a sufficient condition for creating good policy: the impetus for any environmental decision comes from a convergence of science and culture.

A discussion of strategies for communicating models of social-ecological systems inevitably circles back to the importance of incorporating the specific human dimensions of a given system into a model's design from the outset. Models intended for diverse end-users benefit from the involvement of those users in the earliest stages of the modeling process (Grant and Swannack, 2008; Schmolke et al., 2010). Crafting credible model presentations models requires a nuanced understanding of a social setting, its people, and the cultural assumptions behind common practices that mutually shape the system of interest (Hall et al., 2012a). "User confidence in the model, as well as the overall quality of the model, almost always is higher as the result of early and continued dialogue with potential users" (Grant and Swannack, 2008: 92). Models incongruent with a community's shared values, histories, and desired futures are expensive in terms of time and money—litigation, enforcement, education, and other incalculable costs of mistrust. Meaningful models and their presentation make biophysical facts congruent with socio-cultural realities.

For model developers who are trying to overcome audience confusion about key terms, are having difficulties communicating the big picture, or are encountering dissonance created by incongruent pre-existing mental/cultural models, we have offered a set of strategies that modelers can use to ensure model presentations are understandable and meaningful. When modelers listen carefully to target audiences as part of the modeling process, modelers gain a means of anticipating how and why audiences may fail to understand aspects of the model presentation.

Anticipating common obstacles to communicating models and applying techniques of audience analysis to examining audiences' pre-existing cultural models should be as integral to a model's development as de-bugging code. A well-tuned, accessible explanation makes the model concept more socially adoptable. The communication strategies presented here are applicable to any kind of model explanation for diverse audiences. There is, of course, no universal formula for explaining and discussing models. The aim of our synthesis is to encourage reflection about communicating systems models in interdisciplinary and politicized settings, and to offer specific ways in which practitioners of systems-based research can improve their communication.

Acknowledgments

This work was made possible in part by a grant from the U.S. National Park Service and U.S. National Science Foundation (award EPS-0904155) for the Sustainability Solutions Initiative at the University of Maine and additional funds from the Senator George J. Mitchell Center for Environmental and Watershed Research at the University of Maine. The authors would also like to thank Brian Fath, Bill Grant, Tarzan Legovic, Tarla Peterson, Candice Piercy, Molly Reif, and the reviewers, whose comments helped this paper evolve.

References

Abel, T., 2003. Understanding complex human ecosystems: the case of ecotourism on Bonaire. Cons. Ecol. 7, 10.
Aber, J.D., 1997 July. Why don't we believe the models? B. Ecol. Soc. Am., 232–233.
Allen, T.F.H., Zellmer, A.J., Wuennenberg, C.J., 2005. The loss of narrative. In: Cuddington, K., Beisner, B.E. (Eds.), Ecological Paradigms Lost: Routes to Theory Change, Theoretical ecology series. Academic Press, New York, pp. 333–370.
Barnaud, C., Le Page, C., Dumrongrojwatthana, P., Trébuil, G., 2012. Spatial representations are not neutral: lessons from a participatory agent-based modelling process in land-use conflict. Environ. Modell. Softw. 27, 1–10.
Begley, S., 2007 August. The global-warming deniers: the truth about denial. Newsweek 13, 20–27.
Booth Sweeney, L., 2008. Connected Wisdom: Living Stories about Living Systems. Chelsea Green Publishers, White River Junction, VT.
Butzer, K.W., Endfield, G.H., 2012. Critical perspectives on historical collapse. Proc. Natl. Acad. Sci. U. S. A. 109, 3628–3631.
Cash, D.W., Borck, J.C., Patt, A.G., 2006. Countering the loading-dock approach to linking science and decision making. Sci. Technol. Hum. Val. 31, 465–495.
CCSP, 2009. Best practice approaches for characterizing, communicating, and incorporating scientific uncertainty in decisionmaking. In: Granger Morgan, M., Dowlatabadi, H., Henrion, M., Keith, D., Lempert, R., McBride, S., Small, M., Wilbanks, T. (Eds.), A Report by the Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, Washington, D.C.
Clark, W.C., 2007. Sustainability science: a room of its own. Proc. Natl. Acad. Sci. U. S. A. 104, 1737–1738.
Costanza, R., Wainger, L., Folke, C., Mäler, K.-G., 1993. Modeling complex ecological economic systems: toward an evolutionary, dynamic understanding of people and nature. Bioscience 43, 545–555.
Crooks, A., Castle, C., Batty, M., 2008. Key challenges in agent-based modeling for geo-spatial simulation. Comput. Environ. Urban 32, 417–430.
Crutzen, P.J., Stoermer, E.F., 2000. The "anthropocene." Glob. Change. News 41, 12–13.
D'Arcy, J., 1998. Technically Speaking: a Guide for Communicating Complex Information. Battelle Press, Columbus, OH.
Fischhoff, B., 2011. Applying the science of communication to the communication of science. Clim. Change 108, 701–705.
Forrester, J.W., 1969. Urban Dynamics. MIT Press, Cambridge, MA.
Forrester, J.W., 1994 June 27–29. Learning through system dynamics a preparation for the 21st Century. In: Keynote Address for Systems Thinking and Dynamic Modeling Conference for K-12 Education. Concord Academy, Concord, MA.
Fyfe, J.C., Gillett, N.P., Zwiers, F.W., 2013. Overestimated global warming over the past 20 years. Nat. Clim. Change 3, 767–769.
Gilbert, N., 2008. Agent-based Models. Sage, London.

Gilbertz, S., Austin, E.A., Norton, J., Horton, C.C., Hall, D.M., 2011. Wicked wisdoms: illuminations of conceptual capacities among local leaders of the Yellowstone River. Stud. Sociol. Sci. 2, 2.
Gilbertz, S.G., Horton, C.C., Hall, D.M., 2007. Yellowstone River Cultural Inventory. United States Corps of Engineers and the Greater Yellowstone River Conservation District Council.
Glaser, D., Bridges, T.S., 2007. Separating the wheat from the chaff: the effective use of mathematical models as decision tools. Integr. Environ. Assess. Manage 3, 442–449.
Grant, W.E., 1998. Ecology and natural resource management: reflections from a systems perspective. Ecol. Mod. 108, 67–76.
Grant, W.E., Swannack, T.M., 2008. Ecological Modeling: a Common-sense Approach to Theory and Practice. Blackwell, Oxford.
Haff, P.K., 2003. Neogeomorphology, prediction, and the Anthropic landscape. Geophys. Monogr. 135, 15–26.
Hall, D.M., Gilbertz, S.J., Horton, C.C., Peterson, T.R., 2012a. Culture as a means to contextualize policy. J. Environ. Stud. Sci. 2, 222–233.
Hall, D.M., Gilbertz, S.J., Horton, C.C., Peterson, T.R., 2013. Integrating divergent representations of place into decision contexts. In: Stewart, W.P., Williams, D.R., Kruger, L.E. (Eds.), Place-based Conservation: Perspectives from the Social Sciences. Springer, Dordrecht, pp. 121–136.
Hall, D.M., Silka, L., Lindenfeld, L., 2012b. Advancing science and improving quality of place: linking knowledge with action in Maine's sustainability solutions initiative. Maine Policy Rev. 21 (1), 22–29.
Harte, J., 2002 Oct.. Toward a synthesis of the Newtonian and Darwinian worldviews. Phys. Today, 29–34.
Heemskerk, M., Wilson, K., Pavao-Zuckerman, M., 2003. Conceptual models as tools for communication across disciplines. Conserv. Ecol. 7, 8.
Holling, C.S., Berkes, F., Folke, C., 1998. Science, sustainability, and resource management. In: Berkes, F., Folke, C. (Eds.), Linking Social and Ecological Systems. Cambridge University Press, Cambridge, UK, pp. 342–362.
Hooke, R.LeB., 1994. On the efficacy of humans as geomorphic agents. GSA Today 4, 224–225.
Hooke, R.LeB., 2000. On the history of humans as geomorphic agents. Geology 28, 843–846.
Innes, J., 1998. Information in communicative planning. J. Am. Plann. Assoc. 64, 52–64.
Jacobson, R.B., Berkley, J., 2011. Conceptualizing and communicating ecological river restoration. In: Simon, A. (Ed.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools, Geophysical Monograph Series, 194. American Geophysical Union, American Geophysical Union, Washington, D.C, pp. 9–28.
Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Modell. Softw. 21, 602–614.
Jones, N.A., Ross, H., Lynam, T., Perez, P., Leitch, A., 2011. Mental models: an interdisciplinary synthesis of theory and methods. Ecol. Soc. 16, 1.
Kahan, D.M., Braman, D., 2006. Cultural cognition and public policy. Yale Law Policy Rev. 24, 147–170.
Kates, R.W., 2011. What kind of a science is sustainability science? Proc. Natl. Acad. Sci. U. S. A. 108, 19449–19450.
Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., et al., 2001. Sustainability science. Science 292 (5517), 641–642.
Krebs, C.J., 2000. Hypothesis testing in ecology. In: Boitani, L., Fuller, T.K. (Eds.), Research Techniques in Animal Ecology. Columbia University, New York, pp. 1–14.
Latour, B., 2004. Politics of Nature: How to Bring the Sciences into Democracy (C. Porter, Trans.). Harvard University Press, Cambridge, MA.
Manor, J., 1999. The Political Economy of Democratic Decentralization. The World Bank, Washington, D.C.
Mayer, R.E., Anderson, R.B., 1992. The instructive animation: helping students build connections between words and pictures in multimedia learning. J. Educ. Psychol. 84, 444–452.
Meadows, D.H., 2008. In: Wright, D. (Ed.), Thinking in Systems: A Primer. Chelsea Green Publishing, White River Junction, VT.
Metcalf, S.S., Wheeler, E., BenDor, T.K., Lubinski, K.S., Hannon, B.M., 2010. Sharing the floodplain: mediated modeling for environmental management. Environ. Modell. Softw. 25, 1282–1290.
Mooney, C., Kirshenbaum, S., 2009. Unscientific America: How Scientific Illiteracy Threatens Our Future. Basic Books, New York.
Murray, A.B., 2003. Contrasting the goals, strategies, and predictions associated with simplified numerical models and detailed simulations. In: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology, Geophysical Monograph Series, 135American Geophysical Union, Washington, D.C, pp. 151–165.
Murray, A.B., 2007. Reducing model complexity for explanation and prediction. Geomorphology 90, 178–191.
Nisbet, M.C., 2009. Communicating climate change: why frames matter for public engagement. Environ 51 (2), 12–23.
Nisbet, M.C., Mooney, C., 2007. Framing science. Science 316 (5821), 56.
Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proc. Natl. Acad. Sci. U. S. A. 104 (39), 15181–15187.
Ostrom, E., Gardner, R., 1993. Coping with asymmetries in the commons. J. Econ. Perspect. 7 (4), 93–112.
Paolisso, M., 2002. Blue crabs and controversy on the Chesapeake Bay: a cultural model for understanding watermen's reasoning about blue crab management. Hum. Organ 61, 226–239.
Paolisso, M., Dery, N., 2010. A cultural model analysis of Chesapeake Bay oyster restoration. Hum. Organ 69, 169–179.
Peck, S.L., 2000. A tutorial for understanding ecological modeling papers for the nonmodeler. Am. Entomol. 46, 40–49.
Peck, S.L., 2004. Simulation as experiment: a philosophical reassessment for biological modeling. Trends Ecol. Evol. 19 (10), 530–534.
Peterson, T.R., Kenimer, A., Grant, W.E., 2004. Using mediated modeling to facilitate collaborative learning among residents of the San Antonio Watershed, Texas, U.S.A. In: Van de Belt, M. (Ed.), Mediated Modeling: a System Dynamics Approach to Environmental Consensus Building. Island Press, Washington D.C, pp. 136–163.
Pidgeon, N., Fischhoff, B., 2011. The role of social and decision sciences in communicating uncertain climate risks. Nat. Clim. Change 1 (1), 35–41.
Pohl, C., 2011. What is progress in transdisciplinary research? Futures 43 (6), 618–626.
Richards, I.A., 1936. The Philosophy of Rhetoric. Oxford University Press, New York.
Rowan, K.E., 1992. The art of explanation: strategies for enhancing comprehension of science. In: Lewenstein, B. (Ed.), When Science Meets the Public. American Association for the Advancement of Science, Waldorf, MD, pp. 131–143.
Rowan, K.E., 1995. A new pedagogy for explanatory public speaking: why arrangement should not substitute for invention. Comm. Educ. 44, 236–250.
Sarewitz, D., 2004. How science makes environmental controversies worse. Environ. Sci. Pol. 7, 385–403.
Schmolke, A., Thorbek, P., DeAngelis, D.L., Grimm, V., 2010. Ecological models supporting environmental decision making: a strategy for the future. Trends Ecol. Evol. 25, 479–486.
Sokolowski, J.A., Banks, C.M., 2011. Principles of Modelling and Simulation: a Multidisciplinary Approach. John Wiley & Sons, New Jersey.
Swannack, T.M., Grant, W.E., Forstner, M.R.J., 2009b. Projecting population trends of endangered amphibian species in the face of uncertainty: a pattern-oriented approach. Ecol. Mod. 220, 148–159.
Swannack, T.M., Hall, D.M., Grant, W.E., 2009a. National Park Service Socioeconomic Conceptual Modeling Workshop Report. National Park Service Social Science Program.
Talwar, S., Wiek, A., Robinson, J., 2011. User engagement in sustainability research. Sci. Public Pol. 38 (5), 379–390.
Tennyson, R.D., Cocchiarella, M.J., 1986. An empirically based instructional design theory for teaching concepts. Rev. Educ. Psychol. 56, 40–71.
Thompson, J.L., Forester, C.B., Werner, C., Peterson, T.R., 2010. Mediated modeling: using collaborative processes to integrate scientist and stakeholder knowledge about greenhouse gas emissions in an urban ecosystem. Soc. Natur. Resour. 23 (8), 742–757.
van der Leeuw, S.E., 2004. Why model? Cybernet. Syst. 36, 117–128.
van den Belt, M., 2004. Mediated Modeling: a System Dynamics Approach to Environmental Consensus Building. Island Press, Washington D.C.
Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of the earth's ecosystems. Science 277, 494–499.
Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Modell. Softw. 25, 1268–1281.
Westervelt, J.D., Cohen, G.L., 2012. Ecologist-developed Spatially Dynamic Landscape Models. Springer, New York.