Chapter 6

Interdisciplinary Modeling for an Ecosystem Approach to Management in Marine Social-Ecological Systems

Anthony M. Starfield and Astrid Jarre

Abstract

Interdisciplinary research to address global change is essential but inherently difficult. Modeling is a necessary component of many interdisciplinary projects; the way in which modelers approach their work and think about modeling can have a profound effect on the success of the project as a whole. This contribution discusses crucial considerations for interdisciplinary modeling:

1. setting of clear system objectives generated from the interdisciplinary problem;
2. identification of an appropriate level of resolution and its maintenance through all aspects of model design;
3. selection of collaborators genuinely interested in interdisciplinarity while well-grounded in their disciplines;
4. maintained focus on communication;
5. rapid prototyping as an approach to develop the project as understanding increases; and
6. choice of a modeling paradigm that focuses on objectives and leads to a balanced contribution from each discipline.

Frame-based modeling is introduced as an example of a modeling paradigm suitable to address long-term changes in social-ecological systems.

Keywords: Interdisciplinary research, system modeling, model design, rapid prototyping, frame-based model, climate variability, long-term change, fisheries systems

Introduction

Over the past two decades, there has been an increasing emphasis on the need for an ecosystem approach to fisheries management. This approach implies collaboration between

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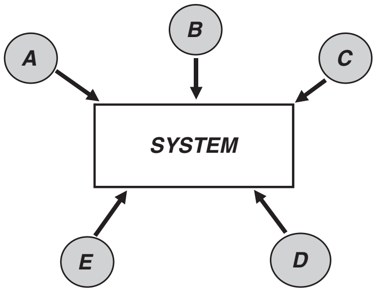
researchers and stakeholders (Neis and Felt, 2000; Degnbol, 2003) as well as between researchers of various disciplines. Multi-disciplinary approaches, which maintain disciplinary boundaries when researching a common problem, have made a first step in getting researchers from various disciplines to learn something about other disciplines (Wilson *et al.*, 2006). Interdisciplinary studies, which draw from various disciplines to work towards a common goal, are increasingly essential, but they are inherently challenging. The disciplines involved in the study are often ill-matched: they may use language differently, have different standards of rigor and accuracy, and may be entrenched in their own paradigms. While all recognize the importance of interdisciplinary work, and funding agencies seem eager to promote such studies, it is often difficult for the individuals involved in them to get appropriate disciplinary recognition for their contribution. Consequently, it is all too easy for interdisciplinary projects to labor ambitiously, intensively, and expensively, but without making a concomitant contribution to the objective, namely (in this case) an increased understanding of the social-ecological system.

In an interdisciplinary project, modelers often have the task of pulling together the various strands and making sense of the whole. However, all too often, modelers are considered to be servants to the project – they have to bow to the expertise of the disciplinarians and the directions of the project leader or leaders – yet the way in which they approach their work and think about modeling can have a profound effect on the success of an interdisciplinary project. For the purpose of this chapter, we define “the modeler” as the person or group of people charged with the development of the model, who can be outsiders to the project or people from inside the project group. The important point is that the modeler has to deliberately take on the role of an independent, outside viewer of the project as a whole. It is the modeler who has to promote a focus on the system as opposed to the focus on its components typically provided by the individual disciplines. It follows that this type of modeling is inherently different from the modeling conducted within the disciplines, such as stock assessment models and oceanographic models. It is our contention that system modeling is key to the success of many interdisciplinary projects because it forces the holistic viewpoint. This chapter therefore looks at interdisciplinary projects from a modeling perspective. It draws heavily on a paper by Nicolson *et al.* (2002) and on a modeling philosophy that can be traced through Starfield and Bleloch (1991), Starfield (1997), and Kettenring *et al.* (2006).

Focusing attention and setting objectives

The following is a list of just some of the keywords we might look for in an interdisciplinary approach to fisheries management: “Ecosystem dynamics, trophic dynamics, global change, oceanography, fish stocks, harvest, by-catch, economics, decision-making under uncertainty, stakeholders, social systems, conflicting objectives.” Not only do the concepts represented by these words cross disciplines, they are also scattered across different temporal and spatial scales. How do we juggle so many ideas at the same time? The answer is to be found by looking at how the human brain deals with complexity. Think of all the information conveyed to the brain at any time by ears and eyes: it filters and ruthlessly ignores most of the incoming information, focusing its attention on what it deems to be important. It is therefore essential for all those involved in an interdisciplinary project, and modelers



Discipline-based approach

Interdisciplinary approach

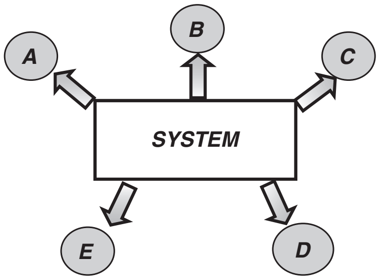


Fig. 6.1 Problem structuring and setting of objectives for an interdisciplinary modeling project. The upper panel illustrates the mode frequently applied: Researchers look at a joint theme, defining objectives from their disciplinary viewpoints. The correct way is illustrated in the lower panel: defining objectives from within the system and then looking to the various disciplines to see how they can contribute towards these objectives.

in particular, to focus attention and concentrate only on what is essential to the project. This chapter offers heuristics and modeling tools for achieving this.

The first step, as always, is to set clear objectives and boundaries. The success of a project or model will rest on how carefully objectives have been set and on making sure that all members of an interdisciplinary team understand the scope of the project and hence, by definition, what is excluded from that scope. Think of an interpreter at a conference: it is much easier to understand and convey what is being said if the context, key points, and boundaries are specified upfront. The usual practice is to ask the disciplinary experts to look at the project from within their disciplines and suggest key objectives. This, as Nicolson *et al*. (2002) point out, is the wrong viewpoint. A good analogy is to think of an orchestra – the players need to follow a score instead of vying for their instruments to be heard individually. The constructive viewpoint is to look for objectives from within the project itself, and only then look out towards the disciplines (Fig. 6.1). This might sound like a trivial distinction, but it is in fact crucial (also see Ommer (2007: Appendix) on the necessity for a shared vision). The interdisciplinary project is a system to be studied or developed. Rooted in their disciplines, experts typically are amateurs with respect to the system itself. We can easily ask the wrong questions starting from within any one discipline. It is essential from the outset to focus attention on the system and develop system-related hypotheses or objectives. Only in this way can we begin to see what is needed for the interdisciplinary project from each discipline. In some cases what is needed will stretch the resources of the disciplinary experts; in other cases it will require the experts to grossly simplify what they know. These distinctions are lost if the system objectives are just the sum of disciplinary objectives.

Clear objectives constrain and focus the always difficult communication between the disciplines. Clear objectives are also the starting point for a model. Unfortunately, clear objectives can be elusive.

A model of a model

Figure 6.2 represents the modeling process. It starts in the top left-hand corner in the box labeled "Real World". This is the complex world where everything is potentially important. The first step is to design a simplified model world that may distort, simplify, or ignore what can be found in the real world. The emphasis here is on the word "design", because what goes into the model world is determined by the objectives of the modeling exercise. Designing the model world is the process of focusing attention. What is left out of the model world goes to a list of assumptions, suppositions, or preferences that are justified in terms of the objectives. The modeler then draws on and shapes the knowledge of the disciplinary experts to build and code the actual model. Again this is a selective and discriminatory process – what the modeler needs to know is defined by the design of the model world, not by everything the disciplinary experts have (and want) to offer. Once the model has been coded, it requires data from the "real world" side of the diagram. These data may or may not be available – remember, "uncertainty" was a keyword. Where data are missing, we can only use the best estimates (or guesses) we can find. It is essential to remember that the design of the model world (and hence of the model) is determined by the objectives, not by the availability of data.

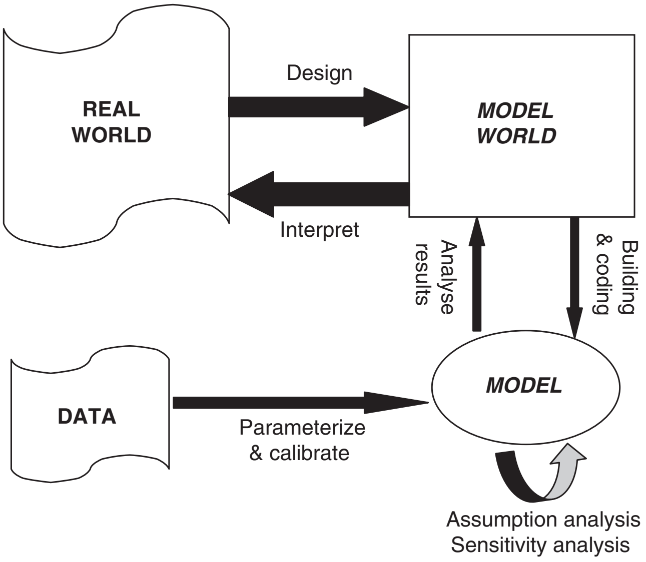


Fig. 6.2 The modeling process. See text for a detailed description.

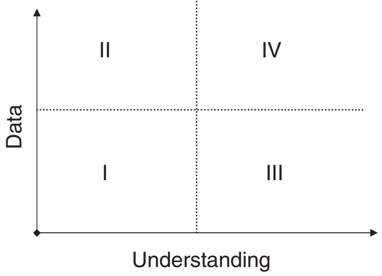


Fig. 6.3 Classification of modeling problems. Interdisciplinary system projects concerned with long-term change typically fit in areas I and III. Area II is the realm of statistical analysis (many fish stock assessment models fit here). Area IV is the domain of the physical sciences. Adapted from Starfield and Bleloch (1991), with permission.

The model is then exercised and produces results. The key point here is that the results relate to the model world; they have to be interpreted back to the real world. Interpretation includes taking into consideration the assumptions of the model and the quality of the data. Notice that this description of the modeling process puts modeling in the same category as a laboratory or field experiment. An experiment is always focused, is always in some sense a simplification, and the results always need to be interpreted. A model is a virtual experiment. Notice too that an “all purpose” model is an oxymoron. The model is shaped by the objectives; broaden them and the model loses shape. Within the context of fisheries, there are disciplinary models such as (single- or multi-species) stock assessment models. Their objectives are almost certainly different from the objectives of an interdisciplinary model in the natural sciences, such as models exploring the effect of environmental variability on plankton communities and the population dynamics of planktivores (Hinckley *et al*., 2001; Ito *et al*., 2007; Megrey *et al*., 2007), or analysing the relative importance of climate variability and fishing effects on offshore fish communities (Travers *et al*., 2006; Shannon *et al*., 2008). During the past three decades, there has been an increase in the number of successful, coupled physical-biological models. However, system models going beyond the natural system, i.e., models linking social and natural systems continue to pose a considerable challenge. Remember that the art of modeling lies in the design of the model, and Holling’s classification of models still applies (Fig. 6.3). As we will attempt to show, it is possible to build useful system models from a general understanding of the structure and functioning of the system, even in the absence of comprehensive datasets.

In this modeling process, it is important to realize that the model will be broken, if any one link in the process is weak or faulty. The chances of finding a weak link are magnified in an interdisciplinary modeling project – there may be confusion in the objectives (leading to an inappropriate model world), imbalance in the model itself, serious gaps in the data, and uncertainty about how to interpret the results.

Rapid prototyping

Rapid prototyping provides a paradigm for dealing with these potential problems. Modelers tend to try to perfect each step in Fig. 6.2 as they follow the process, but this is a mistake. It is far better to build a series of prototypes, with the first prototype built as rapidly as possible. Starting with the objectives in the real world, design the leanest possible model world (if in doubt about a simplifying assumption, make it and note that you have made it), build the model and test it as quickly as you can (using whatever data are readily available and guessing at the rest).

There are several important advantages to developing a quick first prototype:

1. It provides a common "language" and sense of purpose for those participating in the project.
2. It produces preliminary results quickly and gives all participants in an interdisciplinary project a better sense of what the model can do, how the disciplines interact, and where the project may be heading. Even when great care has been taken in setting objectives in the real world, the results of a first prototype model often lead to a reconsideration or refinement of the objectives.
3. The model is not held up by endless arguments about the details of the model world. Since this is only a first prototype, if in doubt, leave it out.
4. Similarly, the exercise is not stalled by poor or missing data.
5. We always learn something new and interesting from a thoughtful modeling exercise, even when the model is very simple.

Many of the points above apply to modeling without prototyping. Van den Belt (2004), for example, shows how to use modeling to educate stakeholders and increase participation in a project. However, prototyping greatly reinforces the advantages of modeling while maintaining focus on the system dynamics.

There are, however, two important steps to be taken with each prototype. The first is to do a thorough sensitivity analysis. Error bounds on the data (and guesses) should be expressed in terms of upper and lower bounds and the model should be tested to see how the results change qualitatively as we switch from one bound to another. A thoughtful sensitivity analysis will help to clarify which data are crucial (and in what way), how much latitude in the data can be tolerated, and what are the consequences of guessing at data that are impossible to obtain. The second step is to do a thorough "assumption analysis" – an assumption analysis is to the assumptions of a model what a sensitivity analysis is to the data. Key assumptions should be tested by modifying the model (in simple ways) to explore how each major assumption may affect the results.

A first prototype with a sensitivity analysis and assumption analysis leads to a reconsideration of the objectives of the project, a clearer understanding of what data are needed, and a good idea of how to improve the model in the next prototype. This review might even lead to the conclusion that the first prototype was heading in the wrong direction and the whole model (perhaps even the whole project) needs to be rethought. Designing for successive prototypes within an interdisciplinary project is the way to keep the whole project focused and in step, and prevents it from careering out of control. At every stage of the project there is a working model (or models); compare this with what (unfortunately) usually happens – nobody sees any results from the modeling effort until right at the very end of a project.

An example of a sensitivity analysis carried out on a simple model – in this case a knowledge-based ("expert") system evaluating the implementation of an Ecosystem Approach to fisheries in the South African sardine fishery – is provided in Paterson *et al*. (2007) and Jarre *et al*. (2008). Smith (2009) shows how to conduct a thorough assumption and sensitivity analysis on a prototype model of climate and fisheries effects on alternating anchovy and sardine dominance regimes in the southern Benguela upwelling marine ecosystem.

The question of balance

Think of your favorite 18th- or early 19th-century painting: it might be a portrait or a landscape or represent a historical event. It will also be balanced in the sense that all quadrants of the canvas are painted in similar and appropriate detail and in the same style. Now take the same painting and imagine that one quadrant is repainted by an impressionist, another by an expressionist, and a third by an abstract artist. The theme remains (if you can detect it) but balance has been lost. Within disciplinary models, there are usually well thought through heuristics on how to achieve balance in model design – a physicist will "know" when to model at the atomic level, and when not. These disciplinary heuristics often fail in an interdisciplinary modeling exercise, just when achieving balance is more crucial than ever. We have to carefully think through what to leave out and what to include in the model, and how to represent what we include; otherwise we lose the rigor of modeling, and hence its value. The objectives of the model guide this process.

Balance is easily lost in interdisciplinary modeling because each of the disciplines "paints" in its own style. A sociologist "sees" a fish population differently from the way an expert in the intricacies of fish stock assessment will see it; biological oceanographers and climatologists would have third and fourth views, and in return, the same diversity of views would apply on the status and dynamics of coastal communities. Moreover, each discipline will "paint" in great detail what is well understood, and will avoid what is needed but not well understood – there are blank patches in your favorite painting! It is the modeler's task to use the objectives of the model to constrain all disciplines to paint in an appropriately similar style. Rapid prototyping helps the modeler to do this.

Where a disciplinary expert would prefer to leave the canvas blank, the modeler needs to coax him or her to paint something (i.e., make some assumptions), given the assurance that this is only a prototype and the assumptions will be probed in an assumption analysis. In this way, an initial flimsy attempt to fill a gap can evolve into something appropriate. Disciplinary experts sometimes push hard to insert their own, often complex, models as "black box" components within the project or system model. It is as though one artist were to say "Leave this corner of the canvas to me and go about the rest of your business." This is unacceptable behavior – it destroys the understanding of the system as a whole and it can very easily knock the system model out of balance. Rapid prototyping discourages this behavior and helps the modeler maintain a balance within each successive prototype. It forces the disciplinary expert to justify what he/she is contributing to the model, and it helps the other disciplinary experts in the project to understand what is going on, to communicate the results among all participants of the project, and to interpret the results coherently in the real world. In the context of marine social-ecological systems, Paterson *et al*. (2010) emphasize the importance of the disciplines meeting on an equal footing; to accomplish this, disciplinary sub-group meetings were used to prepare the appropriate resolution for an integrative model.

The focus in this discussion has been on "the system model", but this definitely does not imply that an interdisciplinary project leads to only one model. In fact, as Nicolson *et al*. (2002) point out, it is important to consider a suite of models, each with its own objectives. The question of balance applies, in different ways, to each of the models.

Frame-based modeling

But how to develop rapid prototype models of something as inherently complex as a marine ecosystem? We need a paradigm that allows us to start with the simplest possible representation of the key aspects of the system dynamics, and then to add detail as needed until we have a model that serves the purpose for which it was built. Frame-based modeling (Starfield and Chapin, 1996; Tester *et al*., 1997) provides this.

Frame-based modeling starts with the State-and-Transition conceptual approach of Westoby *et al*. (1989). We choose an appropriate spatial scale (e.g., the southern Benguela upwelling ecosystem) and imagines how we might characterize, in the broadest possible terms, the state of the system over time. From the viewpoint of the pelagic sub-system, we might choose four states for the southern Benguela, as shown in Fig. 6.4. The next step is to ask how, over time, switches would occur from one state to another. For example, what would precipitate a switch from "Both Low" to "Sardine High, Anchovy Low" in the southern Benguela? All possible switches are identified and the mechanisms and/or events that would precipitate a switch are described. This is as far as the State-and-Transition model goes. It is a conceptual model and does not produce "results", but it serves at least three purposes:

1. It forces the disciplinary experts to look at the system as a whole and boil it down to its essence.
2. It then provides a common "language" for talking about the system and clarifying objectives.
3. It offers, in very broad terms, suggestions for management actions that might help promote the objectives.

For example, Fig. 6.4 might lead to agreement that the "Both High" state is most likely to satisfy both social and economic objectives. Fisheries management should then try to implement strategies that encourage a transition into "Both High" when the system is not in that state, and discourage strategies that lead to a transition out of "Both High" when it is in that state.

This all sounds grossly over-simplified, and indeed it is, but that does not mean that it is not a potentially useful and effective tool for scoping out an ecosystem model. However, it begs to be transformed from a conceptual to a working dynamic model that enables us to quantify and compare various outcomes from alternative management strategies. Frame-based modeling brings about this transformation. We use the word "frame" to replace "state" in talking about Fig. 6.4 and we build a separate dynamic model for each frame. Initially, the purpose of each frame model is to answer only one question: will the system still be in that frame at the end of the next time step, or will it have switched to another

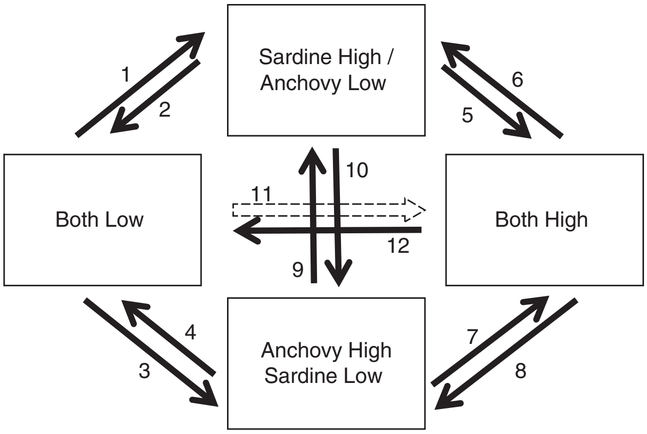


Fig. 6.4 States and transitions in the southern Benguela pelagic upwelling ecosystem as used by Smith (2009). Reproduced with permission. See Table 6.1 for description of arrows.

frame? In other words, the frame model focuses on the arrows leading out of the frame. Once all the independent frame models have been developed, the system model merely provides a mechanism for making sure that at any time the appropriate frame model is being used; it switches out of one frame model into another whenever a transition occurs (Table 6.1).

A trivial example illustrates both the simplicity and power of frame-based modeling. Figure 6.5a represents a student in a class that meets immediately after lunch. There are two frames: the student is "Awake" or "Asleep". The objective of the "Awake" frame model is to decide, at each time step, whether the student is still awake or has switched to the "Asleep" frame. The "Awake" frame model is therefore concerned with variables such as the time since lunch, what the student drank at lunch (strong coffee or a beer?), the temperature in the room, and the monotony of the lecturer's voice. Once the student has switched to the "Asleep" frame, the question changes to "What will cause the student to awaken?" and the considerations will be completely different: does the student have a characteristic afternoon nap duration, or is there a change in activity in the classroom? The first point here is that each frame model deals only with those aspects of the system that are appropriate in that specific frame; when a frame switch occurs, the model changes completely. The second point is that the switches can be triggered by the relatively slow accumulation of quantities (such as time in the "Asleep" frame model) or by more sudden events (such as a loud noise in the room), or even by a combination of the two (the student is impervious to noise in the room at certain times in the sleep cycle). Frame modeling thus combines, very effectively, processes that might operate at different rates with sudden and dramatic events.

Simple frame models can produce complex results. Figure 6.5b extends our example. Suppose our student starts to snore after napping for about 10 minutes. This irritates the football player in the next seat who kicks the student. A gentle kick cause a switch into the Awake frame, but a hard kick breaks a bone and sends the student to a new frame, "Hospital". The student never switches out of the Hospital frame for the purposes of this model, which only describes what happens in the hour of the lecture. We can now see how

Table 6.1 Description of transitions between the frames in Figure 6.4.

Arrow No.	Frameswitch from	Frameswitch to	Conditions for switching
1	Both Low	Sardine High	Weak upwelling (which favours small meso-zooplankton and flagellates). Such conditions are not as favourable to anchovy due to reduced productivity of large diatoms.
2	Sardine High	Both Low	Continued weak upwelling (unfavourable to anchovy recovery) and excessive fishing pressure on sardine – direct sardine fishing or excessive bycatch of juvenile sardine.
3	Both Low	Anchovy High	Continued high fishing pressure on sardine and strong upwelling (which favours diatom growth and is thus good for anchovy). Sardine may also be kept low by sufficient fishing pressure on anchovy due to the increased incidence of juvenile sardine schooling together with anchovy, resulting in increased bycatch of sardine and thus increased mortality of sardine. This behaviour is most noted when the sardine population is already low.
4	Anchovy High	Both Low	Continued fishing pressure on sardine (which inhibits sardine recovery) and deteriorating environmental conditions for anchovy.
5	Sardine High	Both High	Continued low fishing pressure on sardine coupled with improving environmental factors for anchovy recruitment.
6	Both High	Sardine High	Continued low fishing pressure on sardine coupled with deteriorating environmental factors for anchovy recruitment.
7	Anchovy High	Both High	Continued favourable environmental factors for anchovy recruitment and reduced fishing pressure on sardine, allowing for sardine recovery while remaining conducive to anchovy.
8	Both High	Anchovy High	Excessive fishing pressure on sardine and continued favourable environmental factors for anchovy. May be possible if a high anchovy population is fished to such a degree that the juvenile sardine bycatch from the anchovy fishery has a severe impact on the sardine population, even though this level of fishing may not be intolerable for anchovy.
9	Sardine High	Anchovy High	Excessive fishing pressure on sardine and strong upwelling (which favours diatom growth and is thus good for anchovy). Fishing pressure on sardine may be either direct or bycatch-driven.
10	Anchovy High	Sardine High	Low fishing pressure on sardine (which allows stock recovery) and environmental conditions unfavourable for anchovy. Such environmental conditions will enhance sardine recovery.
11	Both Low	Both High	Thought not to be possible. Under a theoretically "favourable for all" situation, the anchovy population should recover faster due to their higher population growth rate and younger age at maturity.
12	Both High	Both Low	Excessive fishing pressure on sardine coupled with deteriorating environmental conditions for anchovy.

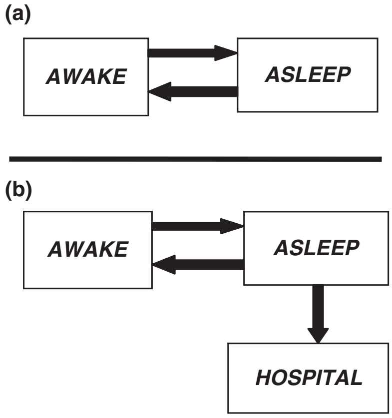


Fig. 6.5 Frame-based model of a student in class. See text for details.

the combination and timing of events in a frame model can lead to complex dynamics. Figure 6.6 gives an example of such dynamics for the southern Benguela.

Frame models can be quantitative or qualitative models. In quantitative models, structure is defined through variables, and dynamics are described using equations. In qualitative models, structure is defined through states, and dynamics through rules. Examples of qualitative system models are given in Starfield *et al*. (1989) and Starfield and Chapin (1996). Frame-based modeling lends itself to rapid prototyping. A very limited effort in research time spent and funding required, compared to major multi-year modeling projects involving large groups of experts (de Young *et al*., 2004), can explore whether or not a model might be useful for the purpose for which it was built. If it is not useful, the mere act of developing and exercising it is likely to lead to a productive conversation and a new approach. If it appears to be useful, sensitivity and assumption analyses will likely suggest what to change or add for the second prototype.

Frame-based modeling also lends itself to exploring how global change might affect the system. (Starfield and Chapin, 1996). Brubaker *et al*. (2009) use the frame-based paradigm for linking paleo-data and model simulation data to develop and test hypotheses about climate-fire-vegetation dynamics over the past 7,000 years. A good example of the use of a frame-based paradigm in interdisciplinary research is Butler *et al*. (2007); they explore the interaction between fluvial dynamics and herbivory on the vegetation adjacent to a river. Perhaps the best example of the use of a frame-based model at the core of an interdisciplinary study involving social scientists as well as biologists is Chapin *et al*. (2008).

People and resources

Nicolson *et al*. (2002) point out some of the problems we can encounter with people and resources in interdisciplinary work. It is worth repeating some of their advice here. The best disciplinary scientists are not necessarily the best interdisciplinary collaborators. Where

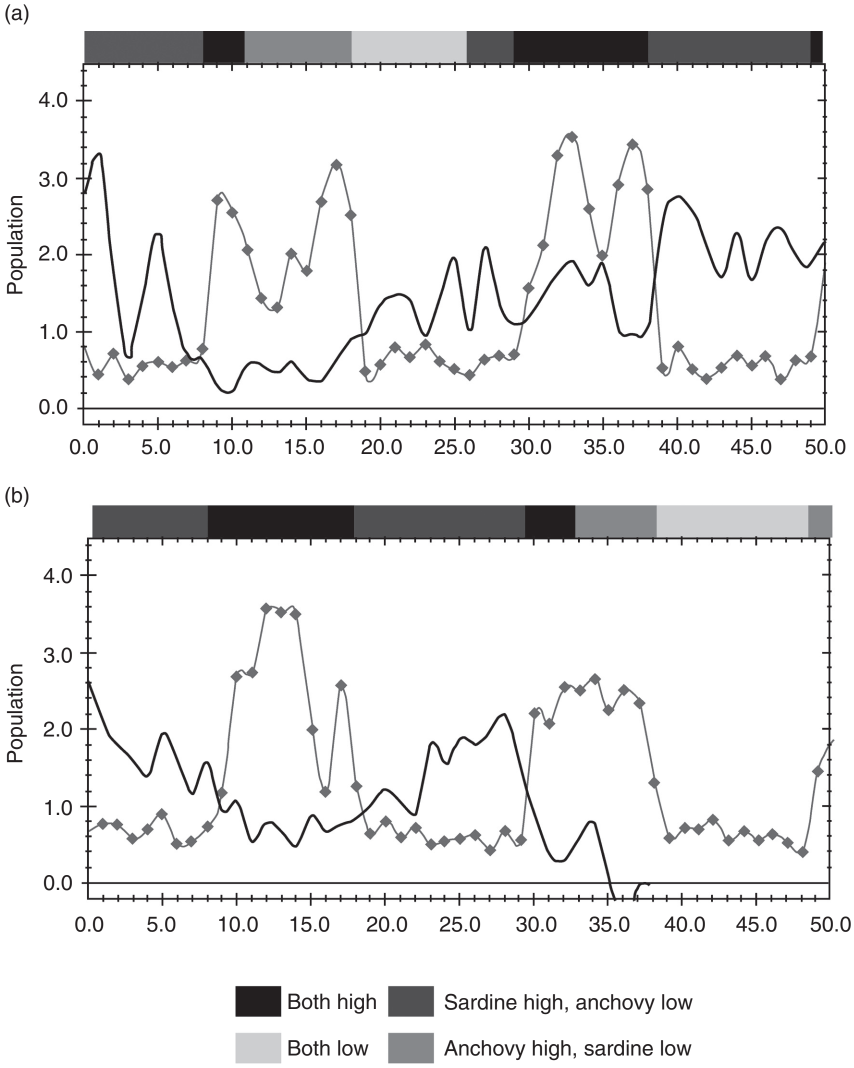


Fig. 6.6 Illustration of the nontrivial dynamics derived from a semi-qualitative frame-based model based on the states and transitions defined in Fig. 6.4 and Table 6.1, and the interplay between an environmental signal and fishing strategies. Sardine trajectory in black (and without points), anchovy in gray (and with points). (a) Sardine fished heavily for 6 years to initiate the steep decline, thereafter fished moderately for the rest of the run. Environmental conditions prevent a recovery for a decade. Under favorable environmental conditions, sardine recovers into a "high" frame and remain high under continued fishing. (b) Sardine fished heavily for 12 years to initiate the steep decline, thereafter fished moderately for the rest of the run. Note that the moderate fishing initiates a sardine recovery in favorable environmental conditions in the third decade, as in (a). From year 30, anchovy is fished heavily in response to high abundance. Bycatch of juvenile sardines in the anchovy fishery initiates sardine stock crash despite continued targeted fishery at moderate levels. Results created using the software developed by Smith (2009).

possible, we need to choose collaborators carefully, looking for people who are like-minded, confident in their discipline, willing to simplify what they know to fit what is needed, and willing to make educated guesses at what they do not know. Unfortunately the ability to simplify what we know, and to fit what we know to the purposes of the project, while leading to a valuable contribution from a disciplinary scientist, may not earn kudos within his or her discipline. It follows that careful thought needs to be given to make sure that interdisciplinary collaborators receive recognition for their work. This is especially important for junior scientists working on such a project.

The modeler (or modeling team) needs to take an independent, outside view of the project in order to achieve the necessary integration. If this is difficult to achieve from within the project, it is necessary (mandatory) to pull in a consultant to provide the outsider's view. With respect to the pelagic fishery in the Benguela, the experience documented in Paterson *et al*. (2010) provides a case in point. Previous experience had made some key disciplinary experts reluctant to join an interdisciplinary project. It took an outsider, in this case an energetic philosopher, to maintain the impetus and provide the ground on which bridges could be built.

It is seldom obvious what will be needed from each participant at the beginning of a project. It follows that it is a mistake to distribute all funds at the start; some funding needs to be held back to use to the best effect as the project develops and the needs become clearer. The idea of distributing some funds and holding back the rest fits well with the paradigm of rapid prototyping. It is an idea that needs to be sold to funding agencies. And, finally, all collaborators need to work hard at communication. It is surprising how easy it is for a scientist in one discipline to say something and for somebody in another discipline to misunderstand what was said, but not know that a misunderstanding had occurred. It is necessary to check that communication really has been effective.

These points are not specific to modeling projects, but pertain to interdisciplinary research as a whole. In the large interdisciplinary research program "Coasts under Stress" (CUS) in Canada, integrative modeling was not carried out, but Ommer (2007, Appendix) highlights the need for the PI, from within the project, to take this outside view and maintain a firm focus on integration across the various contributing disciplines. Likewise, the need to work with and overcome communication difficulties, as well as the restriction of project funding until progress towards the program objectives was documented, formed part of the CUS experience.

Concluding remarks

In summary, the key points in this paper are:

1. Interdisciplinary work needs to be constrained by clear system objectives. The emphasis is on the word "system" because it is a mistake to define objectives from the viewpoint of the disciplines themselves.
2. It is essential to find the appropriate resolution (in the sense of how much detail to include) and to maintain this level of resolution across disciplines. This is what we mean by the word "balance".
3. It is important to choose collaborators carefully, and ensure that collaborators are rewarded for what they contribute to the project.
4. Communication is hard work, and must receive constant attention throughout the project.
5. Rapid prototyping offers a way for collaborators to develop the project as they find out more about it.

6. It is essential to use a modeling paradigm that focuses on objectives and leads to a balanced contribution from each discipline.
7. An effective strategy plans to prototype, interpret results, learn, and move on.

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References

Brubaker, L. B., Higuera, P. E., Rupp, T. S. *et al*. (2009) Linking sediment charcoal records and ecological modeling to understand causes of past fire-regime change in Alaskan boreal forests. *Ecology* **90(7)**, 1788–1901.

Butler, L. G., Kielland, K., Rupp, T. S. *et al*. (2007) Interactive controls by herbivory and fluvial dynamics over landscape vegetation patterns along the Tanana River, interior Alaska. *Journal of Biogeography* **34**, 1622–1631.

Chapin, III, F. S., Trainor, S. F., Huntington, O. *et al*. (2008) Increasing wildfire in Alaska's boreal forest: causes, consequences, and pathways to potential solutions of a wicked problem. *BioScience* **58**, 531–540.

Degnbol, P. (2003) Science and the user perspective: the gap co-management must address. In: *The Fisheries Co- Management Experience: Accomplishments, Challenges and Prospects* (eds D. C. Wilson, J. Raakjaer Nielsen and P. Degnbol), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 31–49.

de Young, B., Heath, M., Werner, F. *et al*. (2004) Challenges of modeling ocean basin ecosystems. *Science* **304**, 1463–1466.

Hinckley, S., Hermann, A. J., Mier, K. L. *et al*. (2001) Importance of spawning location and timing to successful transport to nursery areas: a simulation study of Gulf of Alaska walleye pollock. *ICES Journal of Marine Science* **58(5)**, 1042–1052.

Ito, S. I., Megrey, B. A., Kishi, M. J. *et al*. (2007) On the interannual variability of the growth of Pacific saury (*Cololabis saira*): a simple 3-box model using NEMURO.FISH. *Ecologial Modelling* **202**, 174–183.

Jarre, A., Paterson, B., Moloney, C. L. *et al*. (2008) Knowledge-based systems as decision support tools in an ecosystem approach to fisheries: comparing a fuzzy-logic and a rule-based approach. *Progress in Oceanography* **79**, 390–400.

Kettenring, K. M., Martinez, B. T., Starfield, A. M. *et al*. (2006) Good practices for sharing ecological models. *Bioscience* **56(1)**, 59–64.

Megrey, B. A., Rose, K. A., Klumb, R. A. *et al*. (2007) A bioenergetics-based population dynamics model of Pacific herring (*Clupea harengus pallasi*) coupled to a lower trophic level nutrient-phytoplankton-zooplankton model: description, calibration, and sensitivity analysis. *Ecological Modelling* **202(1–2)**, 144–164.

Neis, B. A. and Felt, L. (2000) *Finding Our Sea Legs*. ISER Books, Memorial University, St Johns NF.

Nicolson, C. R., Starfield, A. M., Kofinas, G. P. *et al*. (2002) Ten heuristics for interdisciplinary modeling projects. *Ecosystems* **5**, 376–384.

Ommer, R. E. (2007) *Coasts under Stress: Restructuring and Social-Ecological Health*. McGill-Queen's University Press, Montreal QC.

Paterson, B., Jarre, A., Moloney, C. L. *et al*. (2007) A fuzzy-logic tool for multicriteria decision-making in the Southern Benguela: the case of the South African sardine fishery. *Journal of Marine and Freshwater Research* **58**, 1056–1068.

Paterson, B., Isaacs, M., Hara, M., Jarre. A. and Moloney, C. L. (2010) Achieving transdisciplinary co-operation for EAF: a South African case study. *Proceedings of the GLOBEC/FAO/EUR-OCEANS Symposium* on "Coping with global change in marine social-ecological systems", *Marine Policy* **34(4)**, 782–794.

Shannon, L. J., Neira, S. and Taylor, M. (2008) Comparing internal and external drivers in the southern Benguela and the southern and northern Humboldt upwelling ecosystems. *African Journal of Marine Science* **30(1)**, 63–84.

Smith, M. D. (2009) Modelling regime shifts in the southern Benguela: a frame-based approach. M. Sc. thesis, Zoology Department, University of Cape Town, South Africa. 102 p.

Starfield, A. M. (1997) A pragmatic approach to modeling for wildlife management. *Journal of Wildlife Management* **61**, 166–174.

Starfield, A. M. and Bleloch, A. L. (1991) *Building Models for Conservation and Wildlife Management*. Interaction Book Company, Edina MN.

Starfield, A. M. and Chapin, III, F. S. (1996) A dynamic model of Arctic and boreal vegetation change in response to global changes in climate and land use. *Ecological Applications* **6(3)**, 842–864.

Starfield, A. M., Farm B. P. and Taylor, R. H. (1989) A rule-based ecological model for the management of an estuarine lake. *Ecological Modelling* **46**, 107–119.

Tester, J. R., Starfield A. M. and Frelich, L. E. (1997) Modeling for ecosystem management in Minnesota pine forests. *Biological Conservation* **80**, 313–324.

Travers, M., Shin, Y. -J., Jennings, S. *et al*. (2006) Towards end-to-end models for investigating the effects of climate and fishing in marine ecosystems. *Progress in Oceanography* **75(4),** 751–770.

Van den Belt, M. (2004) *Mediated Modeling: a System Dynamics Approach to Environmental Consensus Building*. Island Press, Washington DC.

Westoby, M., Walker, B. and Noy-Meir, I. (1989) Opportunistic management for rangelands not at equilibrium. *Journal of Range Management* **42(4),** 266–274.

Wilson, D. C., Raakjær, J. and Degnbol, P. (2006) Local ecological knowledge and practical fisheries management in the tropics: a policy brief. *Marine Policy* **30**, 794–801.