DYNAMIC AQUARIA

Building Living Ecosystems

WALTER H. ADEY KAREN LOVELAND

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PREFACE

This book is an outgrowth of many years of research aimed at studying the problems of accurately modeling complex living ecosystems, particularly aquatic systems. Over the past decade, much of this work was done at the Smithsonian Institution's Marine Systems Laboratory, where one of us (Adey) directed and worked with other scientists in developing new approaches to a growing field with applications extending broadly across modern society.

Today we can build model ecosystems at many scales that are sufficiently similar to their wild counterparts that they allow the dynamic processes that are vital to the survival of hundreds of species, and the ecosystems as a whole. We can construct these working "machines" with modifications of our engineering expertise and with biological and ecological raw material of the wild. We can tinker with them and conduct sophisticated experiments with them to demonstrate what is vital not only to the individual organisms contained in the systems, but also, and perhaps of greater importance, to the operation of the systems as a whole. For it is our ability to work in community with our biosphere that will ultimately determine the quality of our lives. This book provides scientists and professional and amateur aquarists with the opportunity to further their understanding of how to more closely approximate natural ecosystems in artificial environments. We hope it will increase interest in a growing field that needs a high level of research activity.

With our Smithsonian and National Museum of Natural History base, we inevitably have had a core role in public display and education.

Many of our model ecosystems were built at least partly for this function. This taught us that our broader public still has a biological understanding and conservation interest that is strongly directed toward selected species and the exceptional performance or appearance (in human eyes) of some species. Yet, the primary problem with loss of biodiversity today is rarely direct impact on an individual species. Mostly, it is habitat destruction and ecosystem disruption. Only when a broad public appreciates the surrounding world as a collection of functioning ecosystems with hundreds of species of plants, animals, and microbes that support human populations in many ways can we hope to make progress in limiting the degradation of our biosphere. No longer do aquarists have to present individual organisms as captives in totally artificial environments. Functioning ecosystems can be "exhibited" to a public that by and large craves to understand how to be ecologically oriented.

Museum, zoological park and public aquaria are extremely important elements in this ecological educational equation. However, with more than 20 million aquarium hobbyists in the United States alone, the development of hobbist orientation to ecosystems rather than individual species must be a crucial element to public understanding of our biosphere.

The book is divided into four broad sections each containing four to seven chapters. Most chapters begin with a review of the subject matter relative to the bigger picture of ecology, ecosystems, and the earth's biosphere as a whole. Part of our appreciation of the complexities of smaller ecosystems comes from understanding the more universal context in which all ecosystems operate. The remainder of each chapter deals with the building of microcosms and mesocosms of ecosystems for research or public display. Where appropriate, each chapter closes with examples directed to the unique aspects of small home aquarium systems.

Part I discusses the physical environment, elements of which at the ecosystem level have often been greatly misunderstood by the scientist and ignored by aquarists and hobbyists. We discuss our new understanding about the shapes, material, and construction of the envelope that will hold various size aquaria; the temperature, water composition, and motion; solar energy; and the substrate, or rock, mud, and sand that make up the floor of the system and in part provide for all-critical geological storage.

In Part II on the biochemical environment we discuss the mechanisms of gas and nutrient exchange as well as the management of animal wastes in small models. We particularly examine "ecosystem metabolism" contrasting the functions of plants with animals needed for the successful operation of these dynamic ecosystems. We introduce a new means for biochemical management of model ecosystems, using controlled communities of algae, to achieve the simulation of larger volumes of open water and where appropriate, export to other communities or geological storage.

The biological structure section (Part III) stresses the importance of the role of diversity in creating stability in the system. While theoreticians argue as to the why and how of this equation, those of us who work daily with ecosystem models know that greater diversity generally means greater stability. We also introduce a core concept of ecology to aquarium science—the food web. We discuss some of the problems that arise with the compression of community structure and food web dynamics into limited space.

In Part IV we present various case studies of microcosms, mesocosms, and aquaria, including the coral reef mesocosm of the Great Barrier Reef Marine Park in Australia, the Chesapeake Bay and Estuary wetlands, and the Everglades model at the Smithsonian. We also discuss our experience in modeling salt, brackish, and fresh water ecosystems at the aquarium sizes of 70–130 gallons.

Finally, in Part V, we present a series of principles for establishing and operating living ecosystems. This is where the real scientific learning process begins, in reducing our endeavors to core concepts each one of which we strive to better understand in the framework of the ecological function of the natural world. This is also where we truly begin to understand how we human beings can become a vital part of our ecosystems.

As we near the twenty-first century, and our technological horizons continue to expand, we are confronted with new considerations involving the vital interdependency of water and life. As the human race heads off on its greatest adventure yet, the exploration and colonization of space, being able to understand and recreate the earth's ecosystems beyond the confines of our planet is probably a precondition to our ultimate success. The information presented here is perhaps only a step in the realization of this larger dream, but we believe it is a vital link. Artificial habitats in which we choose, for efficiency, only those few elements that we feel comfortable with in an engineering sense, will not likely provide long term, stable life support. For we must look at ecosystems, including those we create, as essential to higher life.

Finally, this book is dedicated to the aquarists of zoological parks and public aquaria around the world. Your efforts in continuing to bring an ever deeper understanding of ecosystems and our biosphere to the broader public can be crucial to the ultimate survival of the human race on this planet.

Walter Adey
Karen Loveland

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ACKNOWLEDGMENTS

This book was conceived within the first few years of the development of the process and basic engineering of algal turf scrubbing. Many times the writing was set aside for a few more years when the further opportunity to try the process with another ecosystem or water quality management or algal production system presented itself. We are therefore indebted to an extraordinary number of individuals and organizations who have helped us bring the book and the model ecosystems it represents to fruition.

First and foremost none of the background research would have been possible without the extraordinary devotion of Walter H. Adey's associates, postdocs, students, and employees. Within the space allotted we can only give credit to a few of the shining lights, among them Susan Brawley, Tim Goertemiller, Jill Johnson, Silvana Campello, Mike Brittsan, Danielle Lucid, John Hackney, Regas Santas, Jim Norris, Matt Finn, Chris Luckett, Donald Spoon, Adam Milton, Janice Bryum, Sue Lutz, and Lynn Ellington. Our sincerest thanks to all of you and to the even larger unnamed group.

Both of us work at an institution justifiably known for the professional freedom it provides. Many of our administrators, especially directors Porter Kier and Paul Johnson, frequently smoothed a path strewn with other obligations so that we could pursue the endeavors that led up to the book itself. Likewise, it was a pleasure to be associated with the Great Barrier Reef Marine Park Authority, and we will always be grateful for the encouragement of its chairman Graeme Kelleher.

For the production of the text and its multitudinous illustrations, we are indebted for the extensive help of artists Charlotte Roland and Alice Jane Lippson and computer graphic specialists Regas Santas, Nina Ahuja, Steven Schloss, and Bradley Tesh. Photographers Nick Caloyianis and Clarita Berger worked tirelessly to achieve needed angles, lighting, and quality results and Mary Ellen McCaffrey, John Steiner, and Louie Thomas of the Smithsonian's Office of Printing and Photographic Services provided high-quality copy work. For administrative follow through, we could not have asked for more than the superb detail work of Addie Fialk and Sarah Hennessey.

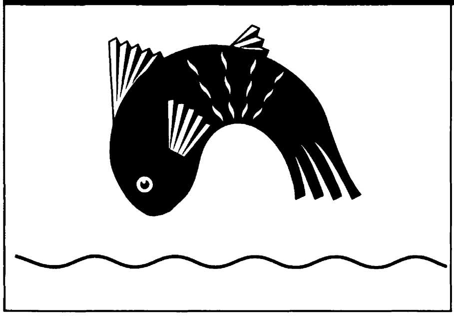
The staff of Academic Press have been so pleasant and supportive that our writing and producing has been a continuing pleasure rather than a task. In particular Jeff Holtmeier, Chuck Arthur, Barbara Heiman, and Barbara Williams were always there helping even when it seemed like we were forever doomed to be late.

Microcosms and mesocosms are expensive to construct, to operate, and to acquire data from. Over the years the Smithsonian Institution, the National Science Foundation, the NOAA Marine Sanctuary Program, and Space Biospheres Ventures have all funded aspects of work presented in this book. We are indebted for their support and hope that in return we have assisted with support of their respective endeavors.

Last, but not least, our respective far flung families have shown only encouragement and patience for a task that consumed our lives. In particular, Nathene Loveland helped us edit for an unfamiliar audience, gave us a sun room to be forever wet, and then held our hands even when sailing was to be preferred.

DYNAMIC AQUARIA

CHAPTER 1



INTRODUCTION

On the surface, water may not appear to be a topic worthy of much discussion. Water is—well, just water. However, on planet Earth there is an tremendous amount of this liquid, and it comprises one of the major spheres that make up our natural world: the hydrosphere (mostly ocean), along with the lithosphere (the rocks and the minerals of the earth's crust), the biosphere (organisms), and the atmosphere (the earth's gaseous envelope). All these concentric envelopes interact with one another. Today most scientists believe that our atmosphere derives its oxygen-rich and low carbon dioxide characteristics directly from plant photosynthesis, and that the hydrosphere, biosphere, and atmosphere are even more inextricably and uniquely intertwined. Indeed, even much of the solid earth's crust was formed or influenced by the activity of water and organisms.

In addition, chemically, water is a most unusual material. By accepted rules, under normal pressures one would expect this ubiquitous compound to exist only as a solid or as a gas, depending on temperature. However, due largely to the peculiar polarization of individual water molecules and the tendency of this compound to form a "semicrystalline" liquid at moderate temperatures, water appears in its most familiar liquid form over a relatively wide temperature range. At the same time, it becomes a "universal" solvent. Almost every chemical element that occurs in the earth's crust dissolves in water, ultimately finding its way into the sea. Here, in the earth's great mixing basin, the potential for the interaction of a wide variety of chemical elements, and the almost infinite number of possible chemical combinations, is significantly increased. The ocean, the ultimate collector of everything washed off the exposed lithosphere and rained out of the atmosphere, becomes very much a chemical soup. One might expect a potential for something very unusual indeed from this infinite number of possible chemical combinations.

Water also has one of the highest capacities of any compound for storing and exchanging heat, and it has great surface tension. Thus, this almost miraculous material is a basic stabilizing element, resisting temperature variations, and tending to become "cellular" by forming internal and external membrane-like surfaces. Given the presence of an additional common chemical element such as carbon, with its great ability to combine with many other elements, the occurrence of liquid water virtually preordains the potential for a chemical complexity that is orders of magnitude above that provided by the basic physical structure of the universe.

Biogenic compounds as complex as amino acids have been identified in interstellar dust and gas clouds, and these may be involved in the collapse that leads to stars and potential solar systems. Nevertheless, without the existence of liquid water, which requires highly specialized conditions (e.g., the right distance from a star or sun, the right planet size, and perhaps even the recycling action of plate tectonics), life cannot develop and continue to evolve (National Research Council, 1990). Wherever liquid water is to be found in the universe in any abundance, life, with its unique ability to store information in a genetic code and to use an energy source for ordering, building, and changing everything with which it comes into contact, is surely to be found. Perhaps somewhere in the vastness of space even more sophisticated life than what we know here on earth occurs.

Billions of years before plants and animals were able to live on land, the first living material formed, evolved, and became ever more complex, as sea organisms. Eventually, along ocean shores and lagoons, perhaps up the numerous rivers, lakes, and wet flats leading to the sea, plants began their first tenuous land existence. Later there followed specially adapted fish capable of crawling on land. As they gradually made the transition to living in an atmosphere rather than floating in the hydrosphere, and as they evolved ways to preserve the crucial water in their bodies from evaporation, plants and animals began to conquer the land. Yet 90% of the time during which life has been on earth has been spent only in the water. And most life that has left the watery environment must conserve and limit its loss of water or die.

Water is the largest component of living matter. While many land plants have developed a form of "suspended" life as nearly dry seeds, at the appropriate time these embryos spring to life as germinating seedlings, but only if water is available. Every animal begins life surrounded by an envelope of fluid. Even land animals, when young, lie in a watery tissue or fluid, protected from the drying air by an encasing shell or by the mother's body. Some scientists believe that the blood that courses through our veins and those of all higher animals is, with some modification, chemically speaking, the equivalent of the ancient sea water that simpler animals used to bring oxygen and food to their cells.

While human adaptation to the terrestrial environment is so complete that living in or even on the ocean has required considerable development of the intellect, we remain fascinated with water and the sea, and constantly strive to truly return to our ancestral home with a new command of that environment. Our engineering accomplishments in this regard are impressive.

The beauty and mystery of lakes, rivers, and oceans have inspired poets and naturalists alike to describe them. But to capture them! That has proven more elusive. For centuries, man has attempted to "bring it back alive"—"it" being a few animals species or occasionally a plant of striking beauty or character. But re-creating the aquatic world, especially the saltwater realm, that would keep those extraordinary creatures alive has often proven difficult.

Communities of organisms residing in freshwater environments are generally less complex than those of the more ancient oceans, making a successful freshwater aquarium considerably easier to achieve. Equally important, those plants and animals are adapted to major and rapid changes in their aquatic piece of the terrestrial world, and therefore are more adaptable to less-than-perfect aquarium environments. Even so, freshwater tanks are a step away from disaster for the unwary who would try to make nature in the small container more than it is in that small piece of the river or lake from which it came, or have failed to provide sufficient elements of wild habitat.

Most home hobbyists and scientists have suffered frustration and often failure in their efforts to establish and maintain marine aquaria. "Witchcraft mixed with a little science" is the way in which one well-known professional aquarist described the difficulties of keeping marine life alive in captivity (Spotte, 1979). An earlier colleague defined the problem as due to the "instability of sea water and its organic constituents, when confined in aquaria or circulatory systems, and to the characteristic inability of marine organisms to adjust to changes in their environment." He listed the necessary components of a proper environment as "a chemically inert water system, a low ratio of animal life to volume of water, the control of bacteria, and the elimination of metabolic waste products" through "aeration, filtration, storage in the dark, and treatment with alkalizers, ultraviolet light and antibiotics" (Atz, 1964).

The concept of the "balanced aquarium" comes to mind as the goal to achieve. Yet, it is curious that the very same concept as applied to wild nature is hardly accepted and has been extensively debated in this century (Egerton, 1973). More recently, "balanced nature" at the species and population level has been replaced not only by a concept of balance but by one of increasing ecological stability with time (extreme physical factors excluded). However, the balance we now find is at the biosphere level (Lovelock, 1979, 1986). In this book we seek the balanced mesocosm, microcosm, or aquarium. However, the balance is at the ecosystem level. Populations may or may not fluctuate in the long term, and because of the relatively small ecosystem sizes involved, human intervention in cropping or replacement of individual organisms is occasionally required to provide the population stability that in the wild is provided by large area.

Over the past few decades, scientists in a variety of laboratories around the world have been making significant advances in keeping marine, estuarine, and aquatic organisms in aquaria-like simulations of real marine environments—model ecosystems, or microcosms. Some of these become quite large, and when they exceed 5000–10,000 gallons in water volume, they are sometimes called mesocosms. There is no sharp line between the microcosm and the aquarium. Perhaps it is best to draw the line at the point where the desire for strict ecosystem simulation is relaxed because of size, and more artificial methods of population or species maintenance, especially human intervention, are undertaken. Living ecosystems in captivity or enclosures have been repeatedly used to answer scientific questions. We will not attempt to develop an historical review but will simply refer to several general works that can lead to the scattered literature for those interested.

In 1984, Eugene Odum called for more mesocosm research, citing overspecialization and fragmentation in ecological research. This paper had been preceded and followed by several compilations of research on aquatic models (Grice and Reeve, 1982), marine and aquatic microcosms (Giesy, 1980), and marine microcosms (Adey, 1987). In the United States, the Marine Ecosystems Research Laboratory at the University of Rhode Island has concentrated on problems of estuarine ecology, especially the fates of pollutants, using a series of cylindrical water towers and a slow flow-through from Narragansett Bay (e.g., Perez *et al.*, 1977; Nixon *et al.*, 1984). More recently, attempts have been made to standardize microcosms as general testing systems for toxic compounds (Gearing, 1989; Taub, 1989). H. T. Odum and R. J. Beyers (1991) review the development and present status of microcosms in scientific research.

Many of these efforts have led to notable scientific insights perhaps unattainable from theoretical or field studies. Although it is not marine or aquatic, but is so exceptional in its accomplishment, we particularly cite microcosm research by Van Voris *et al.* (1980) on an old field community. In this case, the first successful demonstration of an old and very controversial ecological problem, stability versus complexity, was carried out using microcosm techniques. In some cases new organisms of considerable scientific importance have been recognized for the first time in microcosms (e.g., Brawley and Sears, 1981). Indeed, the simplest multicellular animal, *Trichoplax adhaerens*, was first discovered in a marine aquarium and has subsequently become the sole member of a subkingdom of the Kingdom Animalia (Barnes, 1987; Parker, 1982).

In an aquarium context, we have built on the work of Eng (1961) and Risely (1971) as well as many others whose "natural systems" recognize the benefits of a wide diversity of organisms, especially microorganisms, in the marine aquarium. Carlson (1987) undertook a historical review of those aquarists who have sought to develop aquaria capable of keeping stony corals. However, we also draw on the more recent European approaches in freshwater aquaria of including a rich assemblage of plants. We have also attempted to gain a deeper understanding of the processes involved to discover the principles affecting balance in the aquarium as compared to the wild and to formulate the physical, engineering, and biological elements that would lead to successful ecosystem establishment in captivity. Most of the systems we describe, aquatic, estuarine, and marine, are a departure from traditional aquaria in which many important environmental characteristics are omitted and limited numbers of organisms are utilized. Our focus in this book is not on organisms per se, but rather on ecosystem simulation.

There are three basic philosophies of approach used in the management of water quality in closed aquaria and aquatic models. One is abiological, using chemical methods such as ozonation, and physical methods such as physical filtration, protein skimming, and ultraviolet radiation to offset the effects of a basically poor water quality. These methods are almost always used with the second, more generalized technology of bacteriological filtration, which is employed in various forms and has been used in virtually all closed systems of the past 30 years.

The bacteriological (or biological) filter is a device of almost infinite variety used to maximize surfaces with bacterial cultures in close contact with flowing water of the system being managed. The purpose is threefold: (1) the trapping and breakdown of organic particulates; (2) the degradation of the universal waste products urea and highly toxic ammonia to less toxic nitrite and thence to least toxic nitrate; and (3) more recently, either in special anaerobic chambers or in open aerated trickle systems, the denitrification of nitrate nitrogen to atmospheric gas. Either separately or in conjunction with the above systems, oxygen input into the aquarium and carbon dioxide release from the aquarium are maximized to support not only the organisms being maintained, but the essential respiration activity of the bacteria. The intense respiration of the bacteria in these filters releases considerable carbon dioxide, which tends to dangerously acidify the culture. Thus, buffering with calcium carbonate of a wide variety of forms must be used. Moe (1989) provides an excellent summary of modern aquarium methods. In most cases, these methods are sufficient to maintain many organisms. However, rarely do they achieve the quality of unpolluted wild waters. In most cases, the highest quality aquarium water would not meet national minimum standards for wild waters.

The proponents of the basic principles of bacteriological filtration assume that microbes have been the dominant force controlling water quality in the wild. However, this is likely incorrect, since far more organic material is stored in soils and geological sediments than exists in the biosphere. In addition, the earth's atmosphere is rich in oxygen, and prior to human involvement was very poor in carbon dioxide. Plants and algae have created far more organic matter than microbes have degraded, with a concomitant production of oxygen and removal of carbon dioxide from the biosphere. Thus, plants have been and (until humans started burning coal and oil) remain the dominant force controlling earth's chemistry and particularly the needs of higher animals. It is a general tendency of humans to assume that lack of raw materials to maximize production is a basic need that must be managed. In this case, it has been assumed that the primary requirement is rapid breakdown of all organics to basic mineral elements (carbon, nitrogen, phosphorus, sulfur, silica, etc.). We disagree with this concept. While productivity is sometimes limited by the lack of "nutrients," this is not necessarily a bad condition. Excess nutrients usually result in unstable (bloom) conditions in the wild. Farming and aquaculture almost invariably add nutrients so as to drive productivity of a single organism. However, the result is either unstable or semistable, requiring continuous careful management to avoid a variety of "crash" scenarios. Biospheric and ultimately ecosystem stability must lie not in the rapid breakdown of organics but rather in emphasis on their storage as either plant biomass or geological materials. *Stability in the biosphere, in most wild ecosystems, and in microcosms, mesocosms, and aquaria must lie in competition for scarce resources including carbon and nutrients.*

The third philosophy of approach assumes that the primary desire in model ecosystems and aquaria is stability and an environment that is close to that of the wild community being simulated (or at least that from which most of the organisms were drawn). In this case, health of the organisms as a whole rather than maximum productivity of one or a few species is paramount. This approach uses plants, rather than microbes, as the dominant biological controlling element. Since plant photosynthesis and production dominate over animal, bacterial, and plant respiration in this process, nutrients are minimal, controlling and stabilizing, and oxygen is high, often above saturation. In addition, pH is also typically high. It is assumed in systems using plant control of model ecosystem parameters that microbe activity is normal for the ecosystem and that no special approaches are required to increase such activity. Depending on the ecosystem being simulated, the "locking up" of organic reactants (carbon and nutrients) by sedimentation processes may also be a critical element.

Over the past decade we have designed, constructed, and operated microcosm, mesocosm, and aquarium ecosystems in settings as diverse as our home, the laboratories of the Marine Systems Laboratory of the

Smithsonian Institution, and the Great Barrier Reef Marine Park Authority in Townsville, Australia. They have ranged in size from 30 to 750,000 gallons. Some have simulated tropical reefs and lagoons, others subarctic rocky and muddy shore environments, and finally estuaries and rivers. Most have contained hundreds of species. We are now designing a one-million-gallon tropical complex of aquatic ecosystems for a space biosphere, "Biosphere II," in Tucson, Arizona.

The techniques described in this book have enabled us to place complex marine and aquatic microcosms in stable operation in the laboratory as well as the public aquarium. However, many of these systems have also been housed in homemade tanks of plywood, glass, and fiberglass—built on a limited budget, using readily available equipment and materials. More recently, we have developed a series of standard home-size ecological aquaria, 30–150 gallons, some of which are described below.

These approaches have been monitored by sophisticated electronic equipment, and some of the results are described herein. However, extensive instrumentation is not required to construct and operate ecological models once a basic understanding of the system has been acquired. Questions can generally be answered with a few simple measurements or observational techniques. Our home aquaria were purposely developed using the tools available to the home aquarist.

Improved aquarium maintenance and performance through modern techniques can help reduce the enormous losses of organisms in the commercial aquarium trade. The suffering of the animals is deplorable, and there exists the very real possibility that intensive collection will deplete the environment and upset the balance of natural communities. While large numbers of plants and animals may die in the wild during environmental extremes, human impacts in general are becoming severe enough to shift the delicate survival balance negatively for many species and even for ecosystems. For recreation and education purposes, we cannot accept subjecting organisms to stressful conditions beyond their normal environmental range. Even for research purposes, it is crucial that scientists be far more sensitive to the health of the organisms involved and to the potential negative impacts of collecting. The concentration on tropical "reef systems" should cease, and only when the accomplished aquarist has achieved considerable success with less endangered (and equally exciting) ecosystems should a reef community be approached. By adopting ecosystem techniques, distributors, dealers, and hobbyists can maintain functioning systems and reduce losses dramatically. Indeed, experimental ecosystems and their organisms can be maintained separate from wild ecosystems and endangered organisms can be nurtured for return to the wild. Zoological parks have strongly entered into this arena in recent decades, and now public aquaria, with sufficient financial and scientific expertise, can do likewise. Many freshwater fish have been bred in aquaria, and in the past decade increasing numbers of marine species of fish are being added to the list. Because of our success in breeding hundreds of species of aquatic invertebrates and plants in our ecosystem tanks, the prognosis for greatly reducing wild collecting is encouraging.

In the following chapters, we plot an orderly approach to planning and developing microcosms and aquaria. In Part I we first discuss methods of creating the physical environment. Part II treats the chemical environment, which is inseparable from the organisms as physiological elements. The core of the book, Part III, deals with the organisms themselves. They are presented in a food chain or food web format, since the ultimate difficulty in synthetic ecosystems is scaling, a basic problem that is expressed in the way in which food chains are handled. In Part IV we discuss a wide variety of synthetic ecosystems that we have built, or been heavily involved in, ranging from large mesocosms to home aquaria. Finally, in Part V, as a summary, we attempt to express the major elements of the book as a series of steps or principles of synthetic ecology.

We have attempted to direct this book to the professional aquarist and the advanced hobbyist. Hopefully, it will also be of value both for scientists wishing to undertake mesocosm development and for the less advanced but more dedicated hobbyist. There is an extraordinarily large literature for home aquarium management. Much of it is weak and simply a rehash of traditional methodology. A few modern treatments are quite good, in general, though still largely wedded to traditional methods of water treatment. Several of these, particularly Moe, 1989; Hunnam, 1981; Mills, 1986; and Riehl, 1987, are listed among the references given below. This was an old and almost fossilized field that has come alive with new ideas in the past 5–10 years. Some of the best ideas are still in the magazine literature such as *Freshwater and Marine Aquarium* (FAMA) and *Today's Aquarist*. The scientific literature for marine and aquatic mesocosms is likewise extensive, though rather limited in scope. In recent decades, the scientific work has tended toward using ecosystem models for testing the fates of toxic compounds. Several references are listed that can lead to the broader literature. We have specifically tried to avoid extensive literature citation that would reduce the readability of the text. Where material of other authors is used it is cited. When we feel that a particular matter of interest is sufficiently controversial, literature citation is also provided.

Our understanding of the evolutionary relationships of living organisms has been growing by leaps and bounds in the last twenty-five years. To provide some uniformity in a rapidly changing field, we have tried to order all of our taxonomic materials in accordance with Sybil Parker's (1983) *Synopsis and Classification of Living Organisms*. For the reader without a biological background or whose courses in biology predate 1980, we strongly recommend reading *Five Kingdoms* by Margulis and Schwartz (1988).

References

Adey, W. 1987. Marine microcosms. In *Restoration Ecology*. W. Jordan, M. Gilpin, and J. Aber (Eds.). Cambridge University Press, Cambridge.

Atz, J. 1964. Some principles and practices of water management for marine aquariums. In Sea-Water Systems for Experiental Aquariums. J. Clark and R. Clark (Eds.). *Res. Rep.* **63:** 3–16, Bur. Sport Fish. Wildl.

Barnes, R. 1987. *Invertebrate Zoology*, 5th Ed. Saunders, Philadelphia.

Brawley, S., and Sears, J. 1981. Smithsoniella gen. nov., a possible evolutionary link between the multicellular and siphonous habits in the Ulvophyceae, Chlorophyta. *Am. J. Bot.* **69**(9): 1450–1461.

Carlson, B. 1987. Aquarium systems for living corals. *Int. Zool. Yb.* **26:** 1–9.

Egerton, F. 1973. Changing concepts of the balance of nature. *Q. Rev. Biol.* **48:**322–350.

Eng, L. C. 1961. Nature's system of keeping marine fishes. *Trop. Fish. Hobbyist*, Feb. 1961: 23–30.

Gearing, J. 1989. The role of aquatic microcosms in ecotoxicologic research as illustrated by large marine systems. Chapter 15 In S. Levine, M. Harwell, J. Kelly, and K. Kimball (Eds.). *Ecotoxicology: Problems and Approaches.*

Giesy, J. (Ed.). 1980. Microcosms in Ecological Research. U.S. Tech. Inf. Center, U.S. Dept. of Energy, Symp. Ser. 52 (Conf.-781101).

Grice, G., and Reeve, M. (Eds.). 1982. *Marine Mesocosms: Biological and Chemical Research in Experimental Ecosystems.* Springer-Verlag, New York.

Hunnam, P. 1981. *The Living Aquarium.* Ward Lock Ltd., London.

Lovelock, J. 1979. *Gaia, a New Look at Life.* Oxford University Press.

Lovelock, J. 1986. *The Ages of Gaia.* Norton and Co., New York.

Margulis, L., and Schwartz, K. 1988. *The Five Kingdoms.* Freeman, New York.

Mills, D. 1986. *You and Your Aquarium.* Knopf, New York.

Moe, M. 1989. *The Marine Aquarium Reference.* Green Turtle Publications, Plantation, Florida.

National Research Council. 1990. *The Search for Life's Origins. Progress and futue directions in planetary biology and chemical evolution.* National Academy Press, Washington, D.C.

Nixon, S., Pilson, M., Oviatt,C., Donaghay, P., Sullivan, B., Seitzinger, S., Rudnick, D., and Frithsen, J. 1984. Eutrophication of a coastal marine ecosystem—An experimental study using the MERL microcosms. In *Flows of Energy and Materials in Marine Ecosystems.* M. Fasham (Ed.). Plenum Publishing, New York.

Odum, E. 1984. The mesocosm. *Bioscience* **34:** 558–562.

Odum, H. T., and Beyers, R. J. 1991. *Microcosms and Mesocosms in Scientific Research.* Springer-Verlag.

Parker, S. (Ed.). 1982. *Synopsis and Classification of Living Organisms.* McGraw Hill, New York. 2 Vols.

Perez, K., Morrison, G., Lackie, N., Oviatt, C., Nixon, S., Buckley, B., and Heltsche, J. 1977. The importance of physical and biotic scaling to the experimental simulation of a coastal marine ecosystem. *Helgol. wiss. Meeres.* **30:** 144–162.

Riehl, R. 1987. *Aquarium Atlas.* Baensch. Melle, West Germany.

Risely, R. A. 1971. Tropical Marine Aquaria: the Natural System.

Spotte, S. 1979. *Seawater Aquariums.* Wiley, New York.

Taub, F. 1989. Standardized aquatic microcosms. *Environ. Sci. Technol.* **23:** 1064–1066.

Van Voris, P., O'Neill, R., Emanual, W., and Schugart, Jr., H. 1980. Functional complexity and stability. *Ecology* **61:** 1352–1360.

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PART I

Physical Environment

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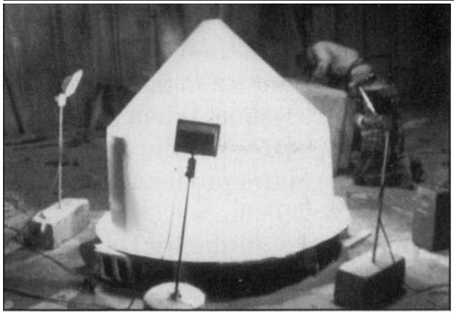
CHAPTER 2



THE ENVELOPE

Shapes, Materials, and Construction

Given ideal environmental conditions, ecosystems require a certain amount of space to fully develop, though quantitatively how much space is a very debatable matter. For example, today, as highways begin to criss-cross the Amazon and its tropical rain forests are rapidly being cleared, we worry that we are rapidly heading toward the lower limits of area that will allow those rain forests and their streams and rivers to continue to exist as complete ecosystems. The remaining more or less wild and protected Florida Everglades occupies over 2000 square miles. Yet it seems clear that it will no longer support a viable population of Florida panthers. The reduced feeding area and perhaps the human disturbance that remains, even under park and reserve protection, keeps the panther from maintaining a population that is large enough to overcome the normal vicissitudes of life. Also, we have known for many decades that the number of plant and animal species that can occur on an island is, to a large extent, a function of island area as well as distance and direction from the nearest source of plant and animal immigration and climate.

Generally, to place an ecosystem in a very large aquarium, terrarium, or other container is not a major ecological problem, though it might well be a considerable engineering endeavor. The difficulty arises when one wishes to scale that ecosystem down and include many components in a much smaller space than that in which they normally occur in the wild.

Thus, to miniaturize an ecosystem, to put it into a small space for pleasure, observation, education, or research, one is immediately faced with a major consideration—how to scale the miniature so that it can still function as a reasonable facsimile of the wild ecosystem. When the model differs from its wild analog, preferably one knows what the differences are. This question is so intimately related to the entire problem of how we affect our wild environments and how we restore them, as well as how we construct our aquaria and terraria, that it requires all the backup discussion of the entire book to approach it properly. This chapter deals primarily with shape and mechanics—how to achieve the physical enclosure once one has decided what the size will be. In the last chapter (Chapter 25), we will return to summarize the questions of how to achieve a functioning ecosystem of some complexity in limited space.

Shape of the Model Ecosystem

There is little biological reason for the traditional box-like aquarium shape. It results primarily from mechanical and esthetic convenience, that is, ease of construction and placement in a room or laboratory. For many scientists and aquarists the ease of purchase and setting up of a ready-made tank outweighs all other factors when a water-based ecosystem is desired. However, to go to the other extreme, if one wished to simulate an accurate planktonic ecosystem in microcosm or mesocosm, the presence of tank walls that would support benthic or bottom communities or would allow excessive lateral daylight or night light would be undesirable. In that case, a weakly translucent cylindrical tank to minimize attachment surface for a given volume, with a continuous, rotating, wiping mechanism, to keep that surface free of settlement, would be a possibility. Such a tank would have to be lighted from the top in such a way that the portion of the photic zone desired would have its appropriate light range over depth in the tank.

For the hobbyist, aquarist, or scientist who wishes to construct a model ecosystem, the materials are now available to do so in any shape. In most cases it is important to set aside the box convention and think first of the ecosystem that one wishes to model. Only after determining the ideal shape for simulation of the desired system should one become concerned about esthetics, viewing, and construction problems. Those concerns may then result in a modification of the ideal shape to a variant of the traditional form.

The modern aquarium tank is typically a box-shaped glass or plastic container with a height of about one-half the length and a width of about one-quarter of the length. A recent tendency is to reduce tank width for improved viewing, or to develop unusual shapes for purely esthetic reasons. Such steps should be carefully considered on an ecological basis,