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Daniel R. Lynch

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SUSTAINABLE NATURAL RESOURCE MANAGEMENT FOR SCIENTISTS AND ENGINEERS

Natural resources support all human productivity. Their sustainable management is among the preeminent problems of the current century. Sustainability and the implied professional responsibility start here. This book uses applied mathematics familiar to undergraduate engineers and scientists to examine natural resource management and its role in framing sustainability. Renewable and nonrenewable resources are covered, along with living and sterile resources. Examples and applications are drawn from petroleum, fisheries, and water resources. Each chapter contains problems illustrating the material. Simple programs in commonly available packages (Excel, MATLAB) support the text and are available for download from the Cambridge University Press website. The material is a natural prelude to more advanced study in ecology, conservation, and population dynamics, as well as engineering and science. The mathematical description is kept within what an undergraduate student in the sciences or engineering would normally be expected to master for natural systems. The purpose is to allow students to confront natural resource problems early in their preparation.

Daniel R. Lynch is the MacLean Professor of Engineering Sciences at Dartmouth College and Adjunct Scientist at the Woods Hole Oceanographic Institution. Through the 1990s he served on the Executive Committee of the US GLOBEC Northwest Atlantic Program and cofounded the Gordon Research Conference in Coastal Ocean Modeling. He has published extensively on finite element methods in coastal oceanography and is coeditor of the AGU volume *Quantitative Skill Assessment for Coastal Ocean Models* and a related volume, *Skill Assessment for Coupled Physical-Biological Models of Marine Systems*, published as a special volume of the *Journal of Marine Systems*. In 2004 he wrote a graduate textbook titled *Numerical Solution of Partial Differential Equations for Environmental Scientists and Engineers: A First Practical Course*. At Dartmouth's Thayer School, Dr. Lynch developed the Numerical Methods Laboratory around the theme of interdisciplinary computational engineering. He pursues research at the intersection of advanced computation and large-scale environmental simulation. Current investigations focus on sustainability, natural resources, and professional education.

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TO BEGIN

... And God saw that it was good. Then God said, “Let us make man in our image, after our own likeness; and let them have dominion over the fish of the sea, and over the birds of the air, and over the cattle, and over all the earth, and over every creeping thing that creeps upon the earth.” So God created man in his own image, in the image of God he created him; male and female he created them. And God blessed them, and God said to them, “Be fruitful and multiply, and fill the earth and subdue it; and have dominion over the fish of the sea and over the birds of the air and over every other living thing that moves upon the earth. ... And God saw everything that he had made, and behold, it was very good.

Genesis 1: 25–28, 31. The Bible, Revised Standard Version

I rode through the “Schroon Country” with a man who has probably done as much as anyone to desolate this whole region ... As league after league of utter desolation unrolled before and around us, we became more and more silent. At last my companion exclaimed: “This whole country’s gone to the devil, hasn’t it?” I asked what was, more than anything else, the reason or cause of it. After long thought he replied: “It all comes to this – it was because there was nobody to think about it, or to do anything about it. We were all busy, and all somewhat to blame perhaps. But it was a large matter, and needed the co-operation of many men, and there was no opening, no place to begin a new order of things here. I could do nothing alone, and my neighbor could do nothing alone, and there was nobody to set us to work together on a plan to have things better; nobody to represent the common object.”

J. B. Harrison, *Garden and Forest* 2:74, July 24, 1889, p 359

Mr. Baker: “As I have talked with thousands of Tennesseans, I have found that the kind of natural environment we bequeath to our children and grandchildren is of paramount importance. If we cannot swim in our lakes and rivers, if we cannot breathe the air God has given us, what other comforts can life offer us?”

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Mr. Muskie: "... Can we afford clean water? Can we afford rivers and lakes and streams and oceans which continue to make life possible on this planet? Can we afford life itself? ... These questions answer themselves. ... Let us close ranks ... so that we can leave to our children rivers and lakes and streams that are at least as clean as we found them, and so that we can begin to repay the debt we owe to the water that has sustained our Nation."

Senators Howard Baker and Edmund Muskie, *Congressional Record*, October 17, 1972

... and He walks in His garden, in the cool of the day

"Now is the Cool of the Day," Jean Ritchie, *A Celebration of Life*, 1971

PREFACE

Natural resources support all human productivity; their sustainable management is among the preeminent problems of the current century. Sustainability, and the implied professional responsibility, starts here.

The primary audiences for this book are scientists and engineers. They are among the people whose professional work directly engages natural resources, whether through harvesting, conversion, or conservation. Constructing a sustainable relationship between natural resources and the human activity they support is a problem that must be embraced by this group of professionals. Accordingly, we use their language – intrinsically scientific and mathematical. And we emphasize quantification and analysis as first principles.

The overall objective of this book is to bring together a unified presentation of natural resources. There are three generic elements:

- Dynamics of the resource in question
- Value of the resource and its uses
- Ownership and “control” of outcomes

or loosely in terms of disciplines: natural science, economics, and political science. Each of these must be blended in any resource analysis. They are the framework of sustainability.

There have been many approaches to this general problem, offering important theories and insights from individual disciplinary perspectives. Among them are harvesting, population structure and dynamics, ecology, land use and geography, economics, water, development, agriculture, forestry, and conservation. Each tradition speaks to a different audience and addresses distinct, specific resource issues, utilizing linear algebra, differential and difference equations, optimization, and computation as needed. The varied use of these analytical tools has been conditioned by the audience and the disciplinary setting. But all of them venture into some similar and overlapping territory in describing key resource concepts (harvest, effort, extraction, extinction, consumption, etc.). It is a goal of this text to present these

ideas in analytical frameworks natural to science and engineering and, by so doing, to engage these professional groups broadly in the problem of sustainable resource management.

Natural Resource Classification. The book is structured within a simple two-way classification, as illustrated in the table below. In the exhaustible category, the basic descriptor is the *amount* *S* of the resource; in the renewable category, the *rate of occurrence* *Q* is paramount. “Sterile” indicates biochemical inactivity, whereas “living” implies self-reproduction. The various quadrants shown are the intersections of these two binary categories:

	Exhaustible S	Renewable Q
Sterile	1 (Oil)	2 (Water)
Living	4 (Fish)	3 (Fish)

Chapter 1 explores the exhaustible sterile category, Quadrant 1, using the example of petroleum throughout. Such a resource will be exhausted eventually; its trajectory is described in terms of the amount available over time. Fundamentally, the resource is finite; some may be undiscovered, but that does not change the facts, only our limited knowledge of them. Discovery is treated as an economic activity, and “Hubbert’s Peak” is found in the intersection of utilization, discovery, and demand expansion. Many fundamental concepts of resource economics are exposed in this quadrant, where the finite supply *S* is the paramount concern. The only sense of sustainability in this quadrant is that associated with the substitute – money invested or knowledge gained – and the legitimacy of the trade-off implied.

Chapters 2, 3, and 4 add the significant feature of self-reproduction: the living resource. Fisheries are the example. As indicated, this case is a hybrid, occupying both Quadrants 3 and 4. *S produces Q*. It is possible to treat such a resource as exhaustible, “mining” *S* to extinction. This risk of extinction is ever present with a living resource, enhanced when growth is slow or highly variable and/or the harvesting is unruly. This case also admits many steady, sustainable states, where the stock *S* is kept constant and the self-renewal rate *Q* is maintained. Hence, sustainable use of a living resource implies sustaining the conditions that support its continued presence and growth; the harvesting activity must be consistent with that sustained presence.

The three chapters present increasing biological sophistication, all the while overlapping Quadrants 3 and 4 and sharing this basic duality. Chapter 2 examines the simplest description in terms of a single biomass variable. It exposes features that endure through Chapters 3 and 4, most notably the need to describe the harvesting effort,

the technology utilized, and the intersection of economic reasoning on the part of the “owner” and the “harvester.” Chapter 3 discusses populations that are structured according to recognizable life stages. Chapter 4 examines the development of cohorts of individuals and concludes with an introduction to individual-based descriptions. A fundamental distinction among these chapters is the way that reproduction is handled. In Chapter 2, it is completely endogenous; Chapter 4 represents it as completely exogenous; and Chapter 3 represents both extremes and helps to put them in context.

Chapter 5 treats the case of the renewable, sterile resource; the standard example is water. In this case, the resource is fundamentally fugitive; S is uncontainable except in very limited amounts and on very short timescales. The rate of occurrence Q is exogenous; we steer Q , but we cannot sequester it for very long.

A third binary axis of classification (not shown in the figure) would be the “degradable/nondegradable” one, where we find the classic case of air or water pollution. **Chapter 6** treats this case in the form of an introduction to pollution and assimilative capacity, building on the networked water description in Chapter 5.

Prerequisites. The present treatment is at the mezzanine (third-year university) level. It requires a first-year university preparation in linear algebra, ordinary differential equations, and computation. Some exposure to operations research and optimization is useful, through linear and mixed-integer programming. That can be introduced here, but ultimately it deserves amplification in separate coursework. Facility with simple computation tools (notably MATLAB and the Excel Solver) is assumed. An exposure to the basic economics of public goods is a valuable supplement. The purpose is to encourage students to confront natural resource problems early in their preparation. At this level, the material has several central themes, which admit a quasi-unified treatment. With this exposure, many in-depth extensions are possible, depending on one’s field of interest.

In the terminology of engineering science, the descriptions use lumped system theory. The optimization is in terms of either the steady states of such systems (e.g., regional water resource systems) or their optimal trajectories (e.g., extraction and exploration histories for nonrenewables). The mathematical description is kept within what an undergraduate student in the physical sciences or engineering would normally be expected to master for other natural systems. The focus is on describing dynamic interactions among resources, economies, and ownership agendas that together determine outcomes. Quantitative mastery of model systems and an ability to transfer those dynamics to realistic contemporary problems are the goals.

This material has been offered to undergraduate Science Division students at Dartmouth College. The lectures form the core of a full course in the topic; they should be supplemented with more descriptive readings according to the instructor’s design and interest.

The lectures are also useful as a set of supplementary examples for teaching the basic mathematics covered, supporting a “natural resources across the curriculum” deployment. Either mode – a stand-alone course or the diffusion of the

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material throughout existing curricula – is an essential beginning in the general area of sustainability.

Software. In terms of computation, the text emphasizes current generic platforms: MATLAB and Excel for its optimization package. These are not intended to be prescriptive, but rather to be usable on portable platforms in the lab, office, or boardroom. There are some elementary programs in each chapter offered as examples for these common platforms. These are summarized at the end of each chapter and are available on the publisher’s Web site: <http://www.cambridge.org/9780521899727>

Audiences. There are several audiences for this book:

1. *Undergraduate students of science and engineering.* These lectures originated in this cohort. The material is a critical foundation for understanding and bringing about sustainability. And, as an integrative introduction, it is a gateway to more advanced study in environmental science and engineering, ecology, and population dynamics, and the intersection of these fields with law, economics, business, public policy, and international development.
2. *Graduate students in professional programs* concerned with the development process, technology management, conservation, and the natural resource/economic/societal interaction. For this audience, undergraduate mathematical study is assumed. Computation is likely to be a most practical and attractive entry point.
3. *Mathematics instructors* in search of lectures treating basic calculus, ODEs, linear algebra, and optimization. The context of natural resources is urgently contemporary. It makes full use of these basic tools and presents a broad front for applied research, particularly in the present context of widespread access to computational power, observational capacity, and networking.

Today, professionals in all walks of life are employing computation on laptops in every setting, with portable programs connecting Web-served databases and information archives to the boardroom. This book projects quantitative natural resource analysis into this arena of common professional activity – a critical step in the implementation of just and sustainable outcomes.

In summary, this text fills the need for a multiresource exposition for undergraduate students of science and engineering. It uses the mathematical preparation already required of these students and introduces many paths into more disciplinary study in ecology, water resources, population dynamics, and resource economics. It is a necessary element in understanding sustainability and the role of science and engineering in achieving it.

Acknowledgments. Many individuals and institutions contributed to this work.

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My colleagues at the Woods Hole Oceanographic Institution, the National Marine Fisheries Service, and the Department of Fisheries and Oceans have been a constant source of inspiration.

Visiting terms were spent at the University of Notre Dame, School of Engineering; the Catholic University of America, School of Philosophy; and Princeton University, Woodrow Wilson School of Public and International Affairs. These were all critical incubation times for the work assembled here, and I am grateful for each of these opportunities.

Finally, words cannot express my appreciation for the support of my immediate family: the bibliophile, the theologian, and the planktoneer. They sustain me, and I dedicate this work to them.

Daniel R. Lynch
Hanover, NH
June 15, 2008