Introduction: Critical Thinking in Environmental Science

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1.1 Critical Thinking is what Counts

This site is intended to develop critical thinking skills that will help you, the student, to become informed participants in environmental decision-making. The site offers specific tools you can use to examine environmental issues with greater clarity, and to disentangle the often abstruse technical arguments in which environmental controversies are often contested. The site aims not so much to achieve environmental literacy in its readers (although that is an admirable goal), but to train people to think clearly about unfamiliar problems in the environment.

Many modern environmental science texts (and thus many of the undergraduate and advanced placement courses that rely on those texts) catalog current environmental issues and increase student literacy about today's environmental problems. They often do less to prepare students to think about tomorrow's, as yet unrecognized, problems. This book reverses that emphasis. Our primary goal in writing this textbook is to train you to think about new or unfamiliar environmental problems. The specific topics we have used to illustrate the thinking skills we wish to develop are secondary, indeed, we encourage teachers and students to look for local environmental controversies where similar thinking skills can be exercised, rather than simply relying on the examples we have developed here.

The issues that lie at the center of environmental debate have changed dramatically over the last twenty five years, and we see no reason to believe such changes will cease. Twenty five years ago few environmental scientists were focusing their attention on loss of biological diversity; it is now a dominant area of research in ecology. Twenty five years ago society at large was just beginning to realize that anthropogenic emissions of carbon dioxide and other greenhouse gasses might have significant effects on global climate; now there are international treaties to ameliorate the greenhouse gas emissions. Within the careers of the environmental scientists being taught today, the spectrum of environmental issues that take central stage in political and social debate will change. New problems will arise either as humans recognize unanticipated problems, as we manage existing problems better or as society comes to think about environmental issues in new ways. While we can not predict with any certainty exactly what topics will occupy environmental scientists a few decades from now, it is likely that a substantial fraction of the issues environmental scientists will address in the decades to come are given little emphasis in today's environmental science texts.

Environmental scientists – and informed lay people thinking about environmental issues – rely most of the time on a relatively small toolkit of critical thinking skills. Those skills can be taught in a progressive manner not only to students with a strong science background, but also to students with only a little prior scientific training. This book, which has evolved out of a course we teach to sophomore Environmental Studies Majors at Bates College, is based on that premise.

1.2 Critical Thinking in Environmental Science

1.2.1 Critical thinking in Environmental Studies

Critical thinking is a skill that can be learned. However, different disciplines have different traditions of what good critical thinking entails. Because environmental issues are strongly interdisciplinary in character, a wide variety of critical thinking approaches can profitably be brought to bear on environmental issues. In considering problems related to global climate change, for example, one could consider them from several perspectives, including (among many others):

- Economic (external costs, time discounting, cost effectiveness of alternative management strategies),
- Political (common property management, international organizations, interest group politics, global governance),
- Historical (How did close relationships between government and industry help build a carbon-intensive economy? Did the modernist belief in material progress exacerbate or reflect widespread carbon use? How are 20^{th} century political conflict and neocolonialism related to carbon emissions?), or
- Scientific (how does CO_2 lead to warming? How much CO_2 is being emitted? How will an altered energy balance of earth alter climate?).

As a practical matter, environmental issues are complex beasts, and it is often profitable to think about them from multiple perspectives. Each perspective has its strengths, and opens up understanding unavailable from other approaches.

Our task with this material, however, is narrower. We wish only to train students to think critically about environmental issues from a technical or scientific perspective. Other approaches are also valuable, and we do not mean to denigrate their importance by not addressing them here. They simply are not the topic of this material.

We identify six critical skills that underlie critical thinking in the environmental science. These are:

1. Healthy skepticism and awareness of political and social biases in oneself and within the environmental science
2. Familiarity with and willingness to use simple quantitative reasoning to tackle unfamiliar problems.
3. Ability to use simple models to formalize thinking about unfamiliar problems
4. Effective use of what you already know to tackle new problems, especially an awareness of how just a few basic scientific laws help clarify problems.
5. Understanding of how variability influences what we know and what we can know about the world around us
6. Ability to think quickly and informally about scientific claims, and especially developing an effective ability to say "that makes sense" or "that sounds implausible" when presented with quantitative estimates.

1.2.1.1 Skepticism in Environmental Science

Relatively few critical thinking skills lie at the heart of most good environmental science. But first and foremost among them is a critical – especially a self-critical – attitude of mind.

Scientific work never springs into being without prior commitments to underlying – generally unspoken and unexamined – values. The values that motivate scientific work are many, including commitment to truth or learning, or to improving the well-being of human societies; belief in progress; an interest in justice; concern for national defense; desire for wealth or fame, and so on. Linkage between such unspoken commitments and scientific practice may be especially strong in environmental science. After all, what separates environmental science from other fields is a focus on "the environment" – a category that carries a heavy freight of political and social meanings.

Like it or not, environmental science is carried out in a profoundly political context. Conflicts and concerns within society over management of natural resources, handling of wastes, and prevention of the loss of biological diversity (among many other issues) motivate science both directly through their influence on the availability of funds for research and indirectly by affecting the types of questions scientists find interesting. In applied environmental science, research may be driven (often funded!) by its relevance to specific political, governmental or managerial interests. Specific laws and regulations mandate other measurements and studies, while scientific opinion can be critical to the outcome of court cases with a bearing on environmental law. In modern western societies, science carries with it considerable prestige, and thus the pronouncements of scientists carry a certain *gravitas* within political debate. Environmental scientists ranging from Rachel Carson to Steven Schneider have made public use of their privileged position as experts, writing popular books, testifying before congressional committees and lobbying legislators to achieve political ends. But equally important, legislators and interest groups both propounding and opposing environmental protection make strategic and tactical use of environmental science.

While political commitments or commitments to unexamined values can lead to distortion of science via fraud or misrepresentation, such cases are relatively rare. A subtler, less corrosive influence of society on the direction and content of environmental science, however, is pervasive. All scientists are embedded in specific scientific, and cultural milieu, making pure objectivity (independent of culture and society) unattainable. A healthy skepticism and a critical attitude constitute the tools for recognizing and evaluating such influences.

The most important target of your critical thinking skills and skepticism should be your own mind. Most students taking an environmental science class would identify themselves as environmentalists. Most faculty teaching such courses would identify themselves that way as well. Both faculty and students come into environmental science courses with their own (our own) distinctive sets of values, assumptions and political biases. These extra-scientific considerations have a profound effect on what questions we ask, what we consider to constitute evidence, and what we come to accept as true. Again, a critical attitude and a healthy skepticism – especially of claims that you are predisposed to believe – constitutes the first requirement of good critical thinking in environmental science.

It is not only true that you cannot believe everything you read. You can't even believe everything you believe.

1.2.1.2 Quantitative Literacy

Like it or not, quantitative thinking forms the basis of most technical discussion of environmental issues. Regulators express emissions standards in quantitative terms – and justify them on the basis of elaborate models of risks to human health. Fisheries scientists rely on mathematical models to determine population levels (and sustainable harvest levels) for fish populations. Engineers use equations that describe aspects of water flow in urban environments to design stormwater management structures. Conservation biologists use population dynamic models to guide management strategies for endangered species. Familiarity with the conventions and principals of quantitative thinking is essential for participating in a large part of today's discussions of environmental issues. If you want to be a full participant in the environmental policy debates in the 21st century, you will need to be able to understand – and criticize – the quantitative arguments marshaled in defense of policy proposals.

Quantitative reasoning has various components, from familiarity with notational conventions to an understanding of various mathematical principals. For our purposes, however, we are defining quantitative literacy in terms of the basic skills that underlie the use of numbers in almost any branch of modern science. These skills precede specific application of quantitative methods, but form the fundamental language of quantitative communication in the sciences. These skills include:

1. Familiarity with common conventions of quantitative presentation in the sciences, such as use of the metric system, scientific notation and significant figures.

2. Facility with broadly applicable quantitative skills such as unit conversions and dimensional analysis

3. Familiarity and a degree of comfort with exponents and logs.

4. Willingness to use quantitative methods and tools when they are appropriate.

1.2.1.3 Use of Models

Basic quantitative literacy as we have defined it prepares one to tackle scientific questions, but real application requires more sophisticated tools. Those tools, which we will call "models", are more discipline or application specific. Ecologists, for example, are often well trained in population dynamics, while hydrologists have a thorough grounding in models of water movement. Environmental chemists, engineers, atmospheric physicists and so on each bring their own particular approach to quantitative thinking.

Models organize scientific thinking, providing tools that clarify understanding, identify key processes or parameters, and (sometimes) make predictions.

Models can be expressed in many ways. Models take conceptual, graphical, or mathematical forms. They can (like models of the chemical structure of DNA) even be physical objects. Increasingly, models are constructed *in silico* – as simulations carried out within a digital computer. Before the wide availability of digital computers, complex dynamical systems were often modeled using complex electrical circuits.

Models and their intelligent utilization form a key part of critical thinking in environmental science. Models permit structured thinking about scientific claims, and thus can help to separate the intellectual wheat from the chaff. But equally important, models aid structured thinking about environmental conditions, the consequences of human activities and implications of proposed environmental policies.

The process of developing or refining a model is often at least as important in developing understanding of environmental processes as is use of a model. Today's global circulation models, for example, are unable to predict global climate in the context of rising atmospheric concentrations of greenhouse gasses such as CO_2 with the geographic specificity needed to clarify long terms social costs and benefits. However, over the past decade, an effort to improve model realism by incorporating more relevant phenomena (from full-ocean circulation to generation of clouds) has dramatically improved our understanding of the coupled ocean-atmosphere system that produces weather and climate. Today, our understanding of the policy choices we face in responding to climate change is much more thorough because of the development, not just the results, of global circulation models.

Models must be used with caution for a very simple reason: All models are wrong. Whether a particular model addresses the dynamics of fish populations, depicts optimal foraging behavior in bees, or addresses reaction rates in chemical reactions, all models are MODELS of the real world. They achieve their power to clarify thinking via simplification. Models direct attention to key phenomena and away from details deemed less significant for the particular problem at hand. Moreover, the correspondence between quantities or concepts expressed in a model and the phenomena they are intended to represent is seldom clear-cut. Each model expresses and idealized, simplified, picture of the world. Thus each model has limited scope. It should only be applied under certain (often unclearly defined) circumstances.

1.2.1.4 Effective Use of What You Already Know

1.2.1.5 Understanding Chance and Variability

1.2.1.5.1 Statistical concepts

1.2.1.5.2 Recognition of the limits to understanding imposed by natural variability

1.2.1.5.3 Experimental or study design and why it is important.

1.2.1.6 Back of the Envelope Thinking

Finally, is an ability to think through a problem informally. Informal thinking in no way substitutes for more formal reasoning, however, it can serve a useful role –especially in complex situations of creating an effective scientific BS filter. If someone tells you, for example, that one gram of botulinum toxin could kill 1 x 10^ 6 people

1.3 Why Material and Energy Flow?

The transport and transformation of matter and the generation and use of energy are key concepts that must frame any technical inquiry into the interactions of humans with the natural world. A major purpose of this textbook is to introduce you to ways of thinking about the major conservation laws and their implications in an environmental context. We want to establish in your consciousness an awareness of these concepts, and provide you with a set of analytic tools that will allow you to ask questions about any process you are interested in – from eutrophication in the lakes of Maine to bioaccumulation of toxic mercury in the food chain.

A plethora of environmental issues exist, all clamoring for people's attention in the global marketplace of ideas. And environmental issues themselves compete for attention, interest, and foundation dollars with issues related to global security, human health, hunger, humanitarian assistance. Over the past two decades, thinkers as diverse as Vandana Shiva, William Cronon, Paul Ehrlich and Herman Daly have repeatedly noted the interpenetration of environmental and social issues. Environmental issues are intimately enfolded with the political and social issues of our time.

Yet in this material, we are focusing not only on environmental issues, but on just a small subset of environmental questions – those that can be examined through the lens of a study of the movement of material or energy through natural and human-dominated dynamic systems. Not every environmental issues is best understood in terms of the movement of material or of energy through complex environmental systems. It is not immediately apparent, for example, how to look at the loss of biological diversity in these terms. We have chosen to focus on movement of materials and energy not because we think issues that can be framed in these terms are more significant than others, but because the focus allows progressive development of the types of critical thinking skills that are the true heart of this book. Moreover, once students have mastered the critical thinking skills we develop here (tied to material and energy flow) they will be much better prepared to extend their technical examination of environmental issues into other areas.

1.4 What is Environmental Science?

1.4.1 The Nature of Environmental Science

You may have been taught in introductory science courses that science progresses by the confrontation of theory with data. According to this positivist view of science, theories that do not correspond with observation are discarded or modified, leading to improved theory. While errors may creep in due to poor scientific practice, fraud, or just plain bad luck, replication of experiments and efforts to test and extend existing ideas give the scientific process a self-correcting character. The positivist model of the scientific process (which dominates the way many practicing scientists think about what they do) posits a sort of intellectual feedback in which successively more accurate or more complete theories succeed one another in a gradual (if perpetually incomplete) approach to understanding or "truth".

If you have been involved with environmental science before taking this course, it may have occurred to you that the positivist description of science applies weakly to much of environmental science. While there are environmental scientists working in research settings to whom construction of new theories or extending our understanding of natural phenomena are central to their work, many environmental scientists work in an applied realm where the neat logical structure of hypothesis testing is followed more in theory than in practice.

Much of what environmental scientists do entails little in the way of hypothesis testing, is seldom motivated by an interest in altering our theoretical understanding of the world and is never replicated. Yet there is a core of "scientific" practice an d thought that lies at the heart of environmental science.

The reason for this is, of course, that environmental science is a fundamentally applied science. At its heart, environmental science is about applying scientific knowledge and methods to environmental problems. Testing theory, even advancing our understanding is often (but by no means always) of secondary importance.

Wetland ecologists routinely evaluate wetlands to enumerate the ecological services they provide to human society – with no interest in altering our understanding of wetland ecosystems, but a great deal of interest in determining how to mitigate the environmental effects of development. Chemists develop and apply sensitive analytic methods to detect part-per-billion concentrations of heavy metals, pesticides or other contaminants in samples of environmental media or living tissues. Yet the majority of such analyses are carried out not to improve scientific understanding, but to support regulatory decisions. Entire sub-disciplines of environmental science, such as risk assessment, are explicitly about clarifying social choices, and not about testing or developing theory. Other important tools in environmental science, such as many complex computer-based simulations, are, as a practical matter, nearly untestable.

For the sake of completeness, we should also mention that the positivist view of science has not been without its challengers. At least since publication of Thomas Kuhn's influential book "The Structure of Scientific Revolutions" in 1962, other conceptions of science have recognized (1) that data is imbued with meaning only in the context of specific theories, and (2) that science is a profoundly social process, in which acceptance of theories depends often on who espouses them, where the ideas were first published, and what social, political and intellectual commitments the theories threaten or support. Thus even the "self-correcting" processes at the heart of science may have embedded or hidden biases. The types of social and political influences on science proposed by Kuhn and his followers are often especially evident in environmental science, because it is explicitly and directly tied to environmental issues.

1.4.2 Role of environmental science within environmental policy

Science is the accepted language of much environmental policy discussion. Science has increasingly become the language of policy analysis. That does not mean that all the underlying issues are scientific, only that much of the debate occurs in the language of science, which means that effective policy makers need to be fluent in the language of science and with scientific methods and ways of thinking.

1.5 Structure of the Site

The site uses a variety of strategies to develop critical thinking skills among students. The site is organized into eight chapters and an extensive data appendix. The first chapter is this introduction, which focuses on the nature of critical thinking in environmental science. The second chapter will review basic skills for mathematical reasoning in the sciences. The third chapter will use a discussion of hydrology and stormwater management issues to introduce modeling and statistical tools you will use throughout the remainder of the book. The remaining chapters each focus on a particular environmental topic and continues to extend your ability to think critically about environmental questions. Chapter four will develop more complex analytic skills, introduce nutrients and nutrient budgets and present energy balance principals with a focus on limnology of and nutrient dynamics in (dimictic) temperate zone lakes. The fifth chapter examines issues of spatial and temporal scale with a focus on the carbon cycle and particularly on efforts to reduce carbon emissions and increase carbon sinks. Chapter six introduces key concepts in risk assessment and a variety of tools for consideration of fate and transport of toxic compounds in the environment by focusing on lead toxicity and the public health problems presented by the legacy of lead use. Chapter seven will apply many of the tools developed in earlier chapters to economic and engineered systems by analysis of anthropogenic systems as transformers and transporters of. Chapter seven will draw the subject matter together, present more complex case studies, challenge students' problem solving skills, and suggest topics and references to which readers might want to turn their attention.

Each chapter includes text that that conveys the basic scientific and technical principals that underlie the chapter, one or more "applications" – in-depth discussion of environmental issues in which the ideas discussed in the chapter play a central role, and a collection of questions and quantitative problems that teachers and students can use to check student understanding and to spur critical thinking. Most chapters also include a brief discussion of potential mathematical modeling exercises and a description of suggested laboratory studies that would complement the material in the text.

The environmental topics for each of the chapters have been selected so that they cover a wide range of spatial and temporal scales. Subjects covered in the course will range from the molecular to the global in scale. We have chosen to span a wide range of scales in order to encourage students to see the connections between scales, and to help students recognize the importance of understanding scale for placing environmental questions in appropriate context.

Throughout the site, we suggest environmentally based estimation exercises to hone your ability to estimate the approximate scale or order of magnitude of environmental phenomena. These might include asking you to estimate – based solely on information you already have – things like the total amount of water flowing through the Boston, Massachusetts sewage treatment system in a day, or the average concentration of mercury in the tissues of freshwater fish in Maine. These "back of the envelope" problems have been central to our course here at Bates College. They serve two purposes. (1) They allow students to practice quantitative thinking in a context in which there are no right or wrong answers – only better and poorer approaches to thinking something through. And (2) they get you to think creatively about solving real-world problems. Please be aware that these problems and the back-of-the-envelope strategies on which they are based are no substitute for in-depth analysis, although they can be great ways to check more detailed calculations.