4th edition

NATURAL RESOURCE AND ENVIRONMENTAL ECONOMICS

ROGER PERMAN   YUE MA   MICHAEL COMMON   DAVID MADDISON   JAMES McGILVRAY

Natural Resource and Environmental Economics

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Natural Resource and Environmental Economics

Fourth Edition

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Contents

Preface to the Fourth Edition

As we wrote in a previous preface, there are two main reasons for producing a new edition of a textbook. First, the subject may have moved on – this has certainly been true in the area of natural resource and environmental economics. Second, experience in using the text may suggest areas for improvement. Both reasons warrant a fourth edition now.

We will say nothing here about the ways in which the subject area has 'moved on' except to note that it has and that you will find those changes reflected in this new edition. As far as experience in the use of this text is concerned, some more comment is warranted.

First, we have received a lot of feedback from users of the text. Much of this has been highly favourable. Indeed, the authors are very pleased to note that its readership has become very broad, a characteristic that has been enhanced by Chinese and Russian translations. User feedback – formal and informal – has provided us with many ideas for ways of making the text better. We are particularly grateful to those individuals who provided solicited reviews of the third edition, and to the many readers who made unsolicited comments. Many of the changes you will find here reflect that body of advice.

The invitation to prepare a fourth edition had an important bonus for the authors of the previous editions: they were able to ask Professor David Maddison to join the authoring team. David accepted the invitation, a decision with which the other authors were very pleased. In addition to adding freshness, additional insights and new perspectives to the book, David joining the authorship means that the average age of its authors has now fallen, which should provide greater security for the long-term future of the text. As environmental economists, sustainability is naturally high on our list of objectives.

The move from third to fourth edition has not altered the structure of this textbook in any significant way: in particular, we have largely retained the previous division into Parts and the clustering of themes. But the content has been substantially altered in several places. As with any new edition, the text incorporates substantial updating of material. This new edition also includes much additional content, both theoretical and empirical. And in line with the demands of readers and suggestions of referees there is a greater emphasis on environmental policy.

The chapter on environmental valuation has been substantially modified by the inclusion of new theoretical and analytical content. The discussion of international trade and the environment – which in the third edition occupied just one part of a chapter dealing with international environmental problems – is now given its own chapter, and covered in far greater depth as befits its importance in environmental and resource economics.

To accommodate the additional text that followed from those changes, we have taken the mathematical appendices out of the printed textbook itself and relocated them on the book's Companion Website. The collection of learning resources on that site is now far more extensive than in earlier editions, and we hope that this can facilitate the process of updating relevant material between future new editions. Further details of changes made in the fourth edition are given in the Introduction.

There are several friends and colleagues the authors would like to thank. We remain grateful to Jack Pezzey for writing an appendix to Chapter 19. Mick Common, Yue Ma, David Maddison and Roger Perman would like to express their gratitude to Alison McGilvray for her continued support and encouragement throughout this revision process. The genesis and early editions of the book owe much to her late husband, Jim. We hope that she would agree that this new edition is one of which Jim would feel proud.

David, Mick, Roger and Yue have succeeded in remaining permanent partners with their wives – Marilena Pollicino, Branwen Common, Val Perman and Hong Lin – despite the increasing burdens of academic life and textbook preparation. Once again, we are grateful to our wives for their help and encouragement.

It would be wrong of us not to express once again our debt to Chris Harrison (now at Cambridge University Press) for his excellence in all aspects of commissioning, editing and providing general support for the first two editions of this book. We know he remains interested in its success. Annette Abel has edited the manuscript with diligence and professionalism, correcting many of our errors and improving the transparency and readability of the text. For this we are very grateful. The staff at Pearson Higher Education, particularly Kate Brewin, Robin Lupton, Carole Drummond, Mary Lince and Gemma Papageorgiou have, as always, been helpful, enthusiastic and professional.

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YUE MA
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MARCH 2011

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It is impossible to fully acknowledge our debt to the many individuals who have developed, and fostered awareness of, the discipline of natural resource and environmental economics. We hope that this debt becomes clear to the reader of this text. What will not be evident to the reader is the debt which the authors owe to those teachers who have cultivated our interests in this area of study.

Wherever the authors have drawn heavily on expositions, in written or other form, of particular individuals or organisations, care was taken to ensure that proper acknowledgement was made at the appropriate places in the text. As noted in the Preface to the Second Edition, Jack Pezzey wrote the first of the appendices to Chapter 19.

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Policy Makers, *IPCC*, Figures 10.4 and 10.29, IPCC, www.ipcc.ch; Figures 9.16 and 9.17 from Working Group III Report 'Mitigation of Climate Change', *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*, Figure 3.17, p. 199 (2007), Source: IPCC, www.ipcc.ch; Figure 9.19 from 'Working Group III, Synthesis Report for Policy Makers', *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*, Figure SPM.8 (2007), Source: IPCC, www.ipcc.ch; Figure 17.9 adapted from *The Handbook of Environmental Economics*, Blackwell (Bromley, D.W. (ed.), 1995) copyright © Blackwell, 1995. Reproduced with permission of Blackwell Publishing Ltd; and Figures 19.3, 19.4 from 'Adjusted Net Savings', The World Bank, February 2009, www.worldbank.org. Source: International Bank for Reconstruction and Development/The World Bank.

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Reproduced by permission of American Economic Association; Table 6.5 adapted from 'Costs of alternative policies for the control of nitrogen dioxide in Baltimore, Maryland', *Journal of Environmental Economics and Management*, vol. 13 (2), Tables II & III pp. 189–97 (Krupnick, A.J., 1986). Copyright © 1986, Elsevier; Table 8.2 from 'A Pilot Study on the Construction of a Scottish Environmental Input–Output System', *Report to Scottish Enterprise, Department of Economics*, University of Strathclyde, Glasgow (McNicoll, I.H. and Blackmore, D., 1993), copyright © Iain McNicoll, University of Strathclyde, Glasgow; Tables 8.3, 8.7, 8.8 adapted from 'Economic modelling and Australian carbon dioxide emissions', *Mathematics and Computers in Simulation*, vol. 33 (5–6), pp. 581–96 (Common, M.S. and Salma, U., 1992). 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Notation

List of variables

As far as possible, in using letters or symbols to denote variables or other quantities of interest, we have tried to use each character consistently to refer to one variable or quantity. This has not always been possible or desirable, however, because of the large number of variables used in the book. In the following listing, we state the meaning that is usually attached to each letter or symbol used in this way. On the few occasions where a symbol is used in two ways, this is also indicated. Where usage differs from those given below, this is made clear in the text.

A	Pollution stock (or ambient pollution level)
B	Gross benefit of an activity
C	Consumption flow *or* total cost of production of a good
D	Damage flow
E	An index of environmental pressure
e	Natural exponent
F	Reduction in pollution stock brought about by clean-up
G	Total extraction cost of a resource *or* biological growth of a resource
H	Renewable resource harvest rate
I	Investment flow
i	Market rate of interest
K	Capital stock (human-made)
L	Labour service flow
M	Emissions (pollution) flow
MP_K	Marginal product of capital
MP_L	Marginal product of labour
MP_R	Marginal product of resource
MU	Marginal utility
MU_X	Marginal utility of good X
NB	Net benefit of an activity
P	Unit price of resource (usually upper-case for gross and lower-case for net)
Q	Aggregate output flow
R	Resource extraction or use flow
r	Consumption discount rate
S	Resource stock
T	Terminal time of a planning period

t	A period or instant of time
U	Utility flow
V	Environmental clean-up expenditure
W	Social welfare flow
Z	Pollution abatement flow
δ	Social rate of return on capital
α	Pollution stock decay rate
ρ	Rate of utility time preference (utility discount rate)

The Greek characters μ, χ and ω are used for shadow prices deriving from optimisation problems.

The symbols X and Y are used in a variety of different ways in the text, depending on the context in question.

Mathematical notation

Where we are considering a function of a single variable such as

$$Y = Y(X)$$

then we write the first derivative in one of the following four equivalent ways:

$$\frac{dY}{dX} = \frac{dY(X)}{dX} = Y'(X) = Y_X$$

Each of these denotes the first derivative of Y with respect to X. In any particular exposition, we choose the form that seems best to convey meaning.

Where we are considering a function of several variables such as the following function of two variables:

$$Z = Z(P, Q)$$

we write first partial derivatives in one of the following equivalent ways:

$$\frac{\partial Z}{\partial P} = \frac{\partial Z(P, Q)}{\partial P} = Z_P$$

each of which is the partial derivative of Z with respect to the variable P.

We frequently use derivatives of variables with respect to time. For example, in the case of the variable S being a function of time, t, the derivative is written in one of the following equivalent forms:

$$\frac{dS}{dt} = \frac{dS(t)}{dt} = \dot{S}$$

Our most common usage is that of dot notation, as in the last term in the equalities above.

Finally, much (but not all) of the mathematical analysis in this text is set in terms of continuous time (rather than discrete time). For reasons of compactness and brevity, we chose in the first, second and third editions to avoid using the more conventional continuous-time notation $x(t)$ and to use instead the form x_t. That convention is continued here. This does, of course, run the risk of ambiguity. However, we have made every effort in the text to make explicit when discrete-time (rather than continuous-time) arguments are being used.

Introduction

Who is this book for?

This book is directed at students of economics, undertaking a specialist course in resource and/or environmental economics. Its primary use is expected to be as a principal textbook in upper-level undergraduate (final year) and taught masters-level postgraduate programmes. However, it will also serve as a main or supporting text for second-year courses (or third-year courses on four-year degree programmes) that have a substantial environmental economics component.

This fourth edition of the text is intended to be comprehensive and contemporary. It deals with all major areas of natural resource and environmental economics. The subject is presented in a way that gives a more rigorous grounding in economic analysis than is common in existing texts at this level. It has been structured to achieve a balance of theory, applications and examples, which is appropriate to a text of this level, and which will be, for most readers, their first systematic analysis of natural resource and environmental economics.

Assumptions we make about the readers of this text

We assume that the reader has a firm grasp of the economic principles covered in the first year of a typical undergraduate economics programme. In particular, it is expected that the reader has a reasonable grounding in microeconomics. However, little knowledge of macroeconomics is necessary for using this textbook. We make extensive use throughout the book of welfare economics. This is often covered in second-year micro courses, and those readers who have previously studied this will find it useful. However, the authors have written the text so that relevant welfare economics theory is developed and explained as the reader goes through the early chapters.

The authors have also assumed that the reader will have a basic knowledge of algebra. The text has been organised so that Parts I to III inclusive (Chapters 1 to 13) make use of calculus only to an elementary level. Part IV (Chapters 14 to 19) deals with the use of environmental resources over time, and so necessarily makes use of some more advanced techniques associated with dynamic optimisation. However, we have been careful to make the text generally accessible, and not to put impediments in the way of those students without substantial mathematics training. To this end, the main presentations of arguments are verbal and intuitive, using graphs as appropriate. Proofs and derivations, where these are thought necessary, are placed in appendices, available from the text's Companion Website. These can be omitted without loss of continuity, or can be revisited in a later reading.

Nevertheless, the authors believe that some mathematical techniques are sufficiently important to an economic analysis of environmental issues at this level to warrant a brief 'first-principles' exposition. We have made available, as freely downloadable documents from the Companion Website, appendices explaining the Lagrange multiplier technique of solving constrained optimisation problems, an exposition of dynamic optimisation and optimal control theory, and a brief primer on elementary matrix algebra.

Contents

As with the third edition, the new fourth edition divides the text into four parts; these parts cluster together the principal areas of interest, research and learning in natural resource and environmental economics.

Part I deals with the foundations of resource and environmental economics

The first chapter provides a background to the study of resource and environmental economics by putting the field in its context in the history of economics, and by briefly outlining the fundamental characteristics of an economics approach to environmental analysis. The text then, in Chapter 2, considers the origins of the sustainability problem by discussing economy–environment interdependence, introducing some principles from environmental science, and by investigating the drivers of environmental impact. Sustainable development is intrinsically related to the quality of human existence, and we review here some of the salient features on the current state of human development. Chapter 3 examines the ethical underpinnings of resource and environmental economics. Part I finishes, in Chapter 4, with a comprehensive review of the theory of static welfare economics, and provides the fundamental economic tools that will be used throughout the rest of the book.

Part II covers what is usually thought to be 'environmental economics'

A principal focus of the six chapters in Part II is the analysis of pollution. We deal here with pollution targets, in Chapter 5, and with methods of attaining pollution targets (that is, instruments), in Chapter 6. We are careful to pay proper attention to the limits of economic analysis in these areas. Pollution policy is beset by problems of limited information and uncertainty, and Chapter 7 is entirely devoted to this matter. Many environmental problems spill over national boundaries, and can only be successfully dealt with by means of international cooperation. Again, we regard this topic of sufficient importance to warrant a chapter, 9, devoted to it. A central feature of this chapter is our use of game theory as the principal tool by which we study the extent and evolution of international cooperation on environmental problems. The spatial incidence of, and perhaps also the aggregate amount of, environmental pollution is affected by the processes associated with international trade; trade and the environment is covered in Chapter 10. Finally, the authors stress the limits of partial equilibrium analysis, and correspondingly the advantages of using system-wide economic analysis. In Chapter 8 we take the reader through the two principal tools of economy-wide economy–environment modelling, input–output analysis and computable general equilibrium modelling. The ways in which general equilibrium – as opposed to partial equilibrium – modelling can enhance our understanding of resource and environmental issues and provide a rich basis for policy analysis are demonstrated here.

Part III is concerned with the principles and practice of project appraisal

Many practitioners will find that their work involves making recommendations about the desirability of particular projects. Cost–benefit analysis is the central tool developed by economists to support this activity. We provide, in Chapter 11, a careful summary of that technique, paying close attention to its theoretical foundations in intertemporal welfare economics. Our exposition also addresses the limits – in principle and in practice – of cost–benefit analysis, and outlines some other approaches to project appraisal, including multi-criteria analysis. A distinguishing characteristic of the economic approach to project appraisal is its insistence on the evaluation of environmental impacts on a basis that allows comparability with the other costs and benefits of the project. In Chapter 12 we examine the economic theory and practice of valuing environmental (and other non-marketed) services, giving examples of the application of each of the more commonly used methods. Inevitably, decisions are made within a setting of risk and uncertainty, and in which actions will often entail irreversible consequences. Chapter 13 examines how these considerations might shape the ways in which projects should be appraised.

Part IV covers what is commonly known as resource economics

The basic economic approach to natural resource exploitation is set out in Chapter 14. In Chapter 15 we focus on non-renewable resources, while Chapter 17 is about the economics of renewable resource harvesting and management, focusing especially on ocean fisheries. Forest resources have some special characteristics, and are the subject of Chapter 18. Chapter 16 revisits the analysis of pollution problems, but this time focusing on stock pollutants, where the analytical methods used to study resources are applicable. In this chapter pollution generation is linked to the extraction and use of natural resources, as is necessary in order to develop a sound understanding of many environmental problems, in particular that of the enhanced greenhouse effect. Finally, Chapter 19 returns to the question of sustainability in the context of a discussion of the theory and practice of environmental accounting.

Perspectives

All books look at their subject matter through one or more 'lenses' and this one is no exception.

- It adopts an *economics* perspective, while nevertheless recognising the limits of a purely economic analysis and the contributions played by other disciplines.
- It is an *environmental* economics (as opposed to an *ecological* economics) text, although the reader will discover something here of what an ecological economics perspective entails.
- The authors have oriented the text around the organising principles of *efficiency* and *sustainability*.
- Many textbook expositions fail to distinguish properly between the notions of efficiency and optimality; it is important to use these related, but nevertheless separate, ideas properly.
- Although the partitioning of the text might be taken to imply a separation of resource economics from environmental economics, our treatment of topics has made every effort to avoid this.
- Some topics and ideas appear at several points in the book, and so are examined from different perspectives and in various contexts. Examples include the Hartwick rule and the safe minimum standard principle.
- Substantial attention is given to the consequences of limited information (or uncertainty) for policy making.

The textbook as a learning resource

The authors are aware that students need a variety of resources for effective learning. Following developments in the previous edition, we have tried to move this fourth edition of the text closer to providing a full set of such resources. This has been done mainly through the development of an accompanying website. Having such a website allows the authors to update content, examples, web link addresses, and so on in a way that is not possible with a printed textbook itself.

The content of that site is described at length in the section on *Additional Resources*. At this point it is sufficient just to note that these consist (principally but not exclusively) of

- appendices to the chapters in the textbook itself. All but five of the chapters in this book have associated with them one or more appendices, amounting to 33 appendices in all. Each of these is a substantial document, often giving a more formal or mathematical treatment of a technique or theme covered in the chapters of the text.
- an extensive set of web links, carefully structured to facilitate further reading and research;
- specimen answers for the Discussion Questions and Problems that appear at the end of the chapters in the book;
- many additional online Word documents, examining at greater length some topics that had relatively brief coverage in the main text (such as biodiversity, agriculture, traffic);
- a large number of Excel files that use simulation techniques to explore environmental issues, problems, or policies. These can be used by the reader to enhance understanding through exploring a topic further; and teachers may work them up into problems that give powerful insight.
- Maple files that one of the authors uses extensively for teaching and research purposes.

Many of our readers will have access to this software package through a university or college with which they are associated. But even where a reader does not have access to Maple software, readable (rich text format) versions of the Maple files will be available, and the structure and techniques used to carry out simulations or to explore environmental issues, problems, or policies will be evident from them. With a little ingenuity, a reader without Maple access should be able to reproduce these exercises using software that can substitute for Maple (such as Mathematica, or one of the freely distributed, public-domain packages such as Maxima).

Other pedagogical features

We have gone to some trouble to use, as far as is possible, consistent notation throughout the book. A list of the main symbols used and their usual meanings is given on pages xx–xxii. However, given the range of material covered it has not been possible to maintain a full one-to-one correspondence between symbols and referents throughout the book. Some symbols do have different meanings in different places. Wherever there is the possibility of confusion we have made explicit what the symbols used mean at that point in the text.

Secondly, each chapter begins with learning objectives and concludes with a chapter summary. While these are relatively modest in extent, we hope the reader will nevertheless find them useful. Finally, each chapter also contains a guide to further reading. Several of these are very extensive. Combined with the website-based links and bibliographies, the reader will find many pointers on where to go next.

Course designs

The authors do, of course, hope that this text will be used for a full course of study involving the material in all 19 chapters. However, we are aware that this would be time-consuming and may not fit with all institutional structures. We therefore offer the following three suggestions as to how the text might be used for shorter courses. Suggestions A and B avoid the chapters where dynamic optimisation techniques need to be used, but still include material on sustainability and the principles and application of cost–benefit analysis. In all cases, courses could be further shortened for students with a strong economics background by treating some parts, at least, of Chapters 4 and 11 as revision material. We do not recommend that this material be completely dropped for any course. Obviously, other permutations are also possible.

A: An environmental economics course

Part I Foundations

Chapter 1 An introduction to natural resource and environmental economics
Chapter 2 The origins of the sustainability problem
Chapter 3 Ethics, economics and the environment
Chapter 4 Welfare economics and the environment

Part II Environmental Pollution

Chapter 5 Pollution control: targets
Chapter 6 Pollution control: instruments
Chapter 9 International environmental problems
Chapter 10 Trade and the environment

Part III Project Appraisal

Chapter 11 Cost–benefit analysis
Chapter 12 Valuing the environment

B: An environmental policy course

Part I Foundations

Chapter 2 The origins of the sustainability problem
Chapter 3 Ethics, economics and the environment
Chapter 4 Welfare economics and the environment

Part II Environmental Pollution

Chapter 5 Pollution control: targets
Chapter 6 Pollution control: instruments
Chapter 7 Pollution policy with imperfect information
Chapter 8 Economy-wide modelling
Chapter 9 International environmental problems
Chapter 10 Trade and the environment

Part III Project Appraisal

Chapter 11 Cost–benefit analysis
Chapter 12 Valuing the environment
Chapter 13 Irreversibility, risk and uncertainty

C: A resource economics and policy course

Part I Foundations

Chapter 2 The origins of the sustainability problem
Chapter 4 Welfare economics and the environment
Chapter 8 Economy-wide modelling

Part III Project Appraisal

Chapter 11 Cost–benefit analysis
Chapter 12 Valuing the environment
Chapter 13 Irreversibility, risk and uncertainty

Part IV Natural Resource Exploitation

Chapter 14 The efficient and optimal use of natural resources
Chapter 15 The theory of optimal resource extraction: non-renewable resources
Chapter 16 Stock pollution problems
Chapter 17 Renewable resources
Chapter 18 Forest resources
Chapter 19 Accounting for the environment

Additional resources

On the back cover of this textbook, you will find the URL (website address) of a site that is available to accompany the text. For convenience, we reproduce the web address again here; it is www.pearsoned.co.uk/perman.

Clicking on this hyperlink will take you to a page on the Pearson website that provides information about Supporting Resources for this textbook. The contents of that page are listed on page i, more fully on pages xxvi–xxvii, and at the foot of this page.

Readers are also encouraged to visit the author's own textbook website at http://personal.strath.ac.uk/r.perman/menu.htm. This accompanying author's website will undergo a process of evolution throughout the life of the textbook. Periodically, the content of the web pages will be reviewed and updated. As errata become known to us, the relevant author's web pages will be periodically updated.

The authors welcome suggestions for further items to include on these web pages. If you would like to make any such suggestion, or if you have a particular 'ready-made' item that you feel would be a useful addition, please e-mail Roger Perman at r.perman@strath.ac.uk. The authors will consider these suggestions carefully and, wherever possible and desirable, incorporate them (with proper attribution) in these web pages.

Supporting resources

Visit **www.pearsoned.co.uk/perman** to find valuable online resources

Companion Website for students

- Additional materials to enhance your knowledge
- Excel files that use simulations techniques to explore environmental issues, problems and policies
- Maple examples and spreadsheet exercises to practise and test your understanding
- Appendices

For instructors

- Complete, downloadable Instructor's Manual
- Answers to questions in the text
- PowerPoint slides that can be downloaded and used for presentations

For more information please contact your local Pearson Education sales representative or visit **www.pearsoned.co.uk/perman**

We now give a little more information about some of the textbook's web-based supporting resources.

Appendices

These are available on the accompanying website but are not in the textbook itself.

- 3.1 The Lagrange multiplier method of solving constrained optimisation problems
- 3.2 Social welfare maximisation
- 4.1 Conditions for efficiency and optimality
- 4.2 Market outcomes
- 4.3 Market failure
- 5.1 Matrix algebra
- 5.2 Spatially differentiated stock pollution: a numerical example
- 6.1 The least-cost theorem and pollution control instruments
- 8.1 A general framework for environmental input–output analysis
- 8.2 The algebra of the two-sector CGE model
- 9.1 Some algebra of international treaties
- 11.1 Conditions for intertemporal efficiency and optimality
- 11.2 Markets and intertemporal allocation
- 12.1 Demand dependency
- 12.2 Weak complementarity with observable Marshallian demand curves
- 13.1 Irreversibility and development: future known
- 13.2 Irreversibility, development and risk
- 14.1 The optimal control problem and its solution using the maximum principle
- 14.2 The optimal solution to the simple exhaustible resource depletion problem
- 14.3 Optimal and efficient extraction or harvesting of a renewable or non-renewable resource in the presence of resource extraction costs
- 15.1 Solution of the multi-period resource depletion model
- 15.2 The monopolist's profit-maximising extraction programme
- 15.3 A worked numerical example
- 17.1 The discrete-time analogue of the continuous time fishery models examined in Chapter 17
- 17.2 Derivation of steady-state equilibrium for an open access fishery and for a private property fishery
- 17.3 The dynamics of renewable resource harvesting
- 18.1 Mathematical derivations
- 18.2 The length of a forest rotation in the infinite rotation model: some comparative statics
- 19.1 National income, the return on wealth, Hartwick's rule and sustainable income
- 19.2 Adjusting national income measurement to account for the environment
- 19.3 Theory for an imperfect economy
- 19.4 The UNSTAT proposals
- 19.5 El Serafy's method for the estimation of the depreciation of natural capital

This set of resources contains downloadable (pdf and Word) versions of the full set of Appendices for the various chapters of the textbook itself. Given that depth of understanding is intrinsically desirable, we would urge all readers of this book to read and study these appendices. Nevertheless, all of the appendices are technical elaborations on matters covered more intuitively in the chapters of the textbook, and the reader should find that his or her ability to understand the content of the text is not dependent on being able to fully grasp appendix material.

Additional Materials

This is intended by the authors to be a very significant resource available to readers. It consists of a set of documents that delve more deeply into some aspects of material covered (perhaps only briefly) in the book itself, or which provide more information on the policy or institutional facets of issues in natural resource and environmental economics, or which allow the reader (or an instructor) to undertake model simulations or carry our comparative static or comparative dynamic analysis. These additional materials are intended to be entirely optional and genuinely additional. It is not necessary for the reader to read, study, or work through any of them. It is not required that you use any of these materials to follow any of the arguments and/or examples used in the text. The textbook has been written in such a way that it stands alone, and does not intrinsically depend on these additional materials. (Where we felt something was necessary, it was included in the main text.)

However, the fact that we have included these materials does imply that the authors think you may find some of them useful. Some materials are designed to broaden knowledge (by giving, in Word files, additional commentary on related matters). Others are aimed at deepening understanding by using standard software packages (such as Excel) to show how numerical examples used in the text were obtained, and to allow the reader to experiment a little, perhaps by changing parameter values from those used in the text and observing what happens. Occasionally we use the symbolic mathematical package Maple for some of the items in *Additional Materials*. Many readers will be unfamiliar with this package, and you should not worry if they are not, therefore, useful to you. But please note that Maple is increasingly being used in higher education, is not difficult to learn, and can be a very powerful tool to have at your disposal. You may wish to follow some of our suggestions about learning how to use this package.

Finally, we also anticipate that some lecturers and instructors will wish to adapt some of these materials for class use (much as many of the files you will find here benefit from other writers' earlier work). The authors believe that much useful learning can take place if instructors adapt some of the spreadsheet exercises as exploratory problems and set them as individual or group tasks for their students.

Accessing the Additional Materials

Most of the chapters in the textbook refer to one or more files that are called *Additional Materials*, plus a specific file name.

Some of the *Additional Materials* are available from the Pearson website; others are available from the author's own web pages.

Answers to Questions in the Text

All chapters in this textbook (except the first) contain a small number of Discussion Questions and Problems. Answers to most of these are available. Those answers are collated chapter by chapter, and can be accessed through the main table that you will find on this web page.

Environmental Economics Links

As we remarked in the third edition, a huge volume of information of interest to the environmental economist can now be found on the Internet. This can be read online, printed for future reference or saved to disk. It is hardly a novel idea to compile a set of 'Useful links' and to place this on one's own website. We have also done that. You will find these web links on the author's own website at http://personal.strath.ac.uk/r.perman/menu.htm.

However, we have reasons for believing you may find this one more useful than most. The main reason for this belief lies in its structure. Actually, these links are structured in two different ways:

- by chapter topic;
- by the provider type.

For example, suppose that you have just read Chapter 17 (on renewable resources) and wish to be pointed to a set of web links that are particularly useful in relation to the content of that chapter. Then go to the chapter-by-chapter menu option, select 17 from the table, and the links will be provided. We do not claim that our classification is always uncontentious; but the authors have tried to be helpful. Some of the web links contain brief annotated commentary that may help you select more efficiently.

The 'By organisation link' structure is more conventional but still very useful, given that so much of value comes from a relatively small set of organisations. You will find that we have further sub-classified this set in various ways to help your searching. It will be too cumbersome to explain the classification structure here. It will be much simpler for you to follow the appropriate link from the Main Menu and view it directly. You will no doubt know already many incredibly good Internet sites maintained by organisations with an interest in the environment (such as those of the US EPA, various United Nations bodies, and many environmental ministries). You may be less aware of the existence of a large number of excellent university or research group sites, or those of various individuals and non-governmental organisations (NGOs).

Note also that the main menu has one specific item labelled as 'A variety of Bibliographies'. Listed here are not only links to some excellent printed book and/or article bibliographies but also links to a small number of other exceptionally good website compilations. You do not have to rely only on us, therefore!

We are always looking for new suggestions for links to be included in our lists. Please e-mail suggestions to Roger Perman (address given earlier).

Site availability

The URL for the accompanying companion website maintained by Pearson is www.pearsoned.co.uk/perman. However, some of the materials that are associated with this textbook are updated on a regular basis and are only to be found on Roger Perman's personal website for this textbook, on a server located at the University of Strathclyde. This can be accessed via the URL http://personal.strath.ac.uk/r.perman/menu.htm. In common with web addresses at many university servers, this address may change at some time in the future. In the event of such a change, a link to the revised address will be given on the accompanying website.

PART I Foundations

CHAPTER 1 An introduction to natural resource and environmental economics

Contemplation of the world's disappearing supplies of minerals, forests, and other exhaustible assets has led to demands for regulation of their exploitation. The feeling that these products are now too cheap for the good of future generations, that they are being selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed wastefully has given rise to the conservation movement.

Hotelling (1931)

Learning objectives

In this chapter you will

- be introduced to the concepts of efficiency, optimality and sustainability
- learn about the history of natural resource and environmental economics
- have the main issues of modern resource and environmental economics identified
- see an overview and outline of the structure of this text

Introduction

The three themes that run through this book are efficiency, optimality and sustainability. In this chapter we briefly explain these themes, and then look at the emergence of the field of study which is the economic analysis of natural resources and the environment. We then identify some of the key features of that field of study, and indicate where, later in the book, the matters raised here are discussed more fully.

1.1 Three themes

The concepts of efficiency and optimality are used in specific ways in economic analysis. We will be discussing this at some length in Chapter 4. However, a brief intuitive account here will be useful. One way of thinking about efficiency is in terms of missed opportunities. If resource use is wasteful in some way then opportunities are being squandered; eliminating that waste (or inefficiency) can bring net benefits to some group of people. An example is energy inefficiency. It is often argued that much energy is produced or used inefficiently, and that if different techniques were employed significant resource savings could be gained with no loss in terms of final output.

This kind of argument usually refers to some kind of technical or physical inefficiency. Economists usually assume away this kind of inefficiency, and focus on allocative inefficiencies. Even where resources are used in technically efficient ways, net benefits are sometimes squandered. For example, suppose that electricity can be, in technically efficient ways, generated by the burning of either some heavily polluting fossil fuel, such as coal, or a less polluting alternative fossil fuel, such as gas. Because of a lower price for the former fuel, it is chosen by profit-maximising electricity producers. However, the pollution results in damages which necessitate expenditure on health care and clean-up operations. These expenditures, not borne by the electricity supplier, may exceed the cost saving that electricity producers obtain from using coal.

If this happens there is an inefficiency that results from resource allocation choices even where there are no technical inefficiencies. Society as a whole would obtain positive net benefits if the less polluting alternative were used. We show throughout the book that such allocative inefficiencies will be pervasive in the use of natural and environmental resources in pure market economies. A substantial part of environmental economics is concerned with how economies might avoid inefficiencies in the allocation and use of natural and environmental resources.

The second concept – optimality – is related to efficiency, but is distinct from it. To understand the idea of optimality we need to have in mind:

1. a group of people taken to be the relevant 'society';
2. some overall objective that this society has, and in terms of which we can measure the extent to which some resource-use decision is desirable from that society's point of view.

Then a resource-use choice is socially optimal if it maximises that objective given any relevant constraints that may be operating.

As we shall see (particularly in Chapter 4), the reason efficiency and optimality are related is that it turns out to be the case that a resource allocation cannot be optimal unless it is efficient. That is, efficiency is a necessary condition for optimality. This should be intuitively obvious: if society squanders opportunities, then it cannot be maximising its objective (whatever that might be). However, efficiency is not a sufficient condition for optimality; in other words, even if a resource allocation is efficient, it may not be socially optimal. This arises because there will almost always be a multiplicity of different efficient resource allocations, but only one of those will be 'best' from a social point of view. Not surprisingly, the idea of optimality also plays a role in economic analysis.

The third theme is sustainability. For the moment we can say that sustainability involves taking care of posterity. Why this is something that we need to consider in the context of resource and environmental economics is something that we will discuss in the next chapter. Exactly what 'taking care of posterity' might mean is discussed in Chapter 3. On first thinking about this, you might suspect that, given optimality, a concept such as sustainability is redundant. If an allocation of resources is socially optimal, then surely it must also be sustainable? If sustainability matters, then presumably it would enter into the list of society's objectives and would get taken care of in achieving optimality. Things are not quite so straightforward. The pursuit of optimality as usually considered in economics will not necessarily take adequate care of posterity. If taking care of posterity is seen as a moral obligation, then the pursuit of optimality as economists usually specify it will need to be constrained by a sustainability requirement.

1.2 The emergence of resource and environmental economics

We now briefly examine the development of resource and environmental economics from the time of the industrial revolution in Europe.

1.2.1 Classical economics: the contributions of Smith, Malthus, Ricardo and Mill to the development of natural resource economics

While the emergence of natural resource and environmental economics as a distinct sub-discipline has been a relatively recent event, concern with the substance of natural resource and environmental issues has much earlier antecedents. It is evident, for example, in the writings of the classical economists, for whom it was a major concern. The label 'classical' identifies a number of economists writing in the eighteenth and nineteenth centuries, a period during which the industrial revolution was taking place (at least in much of Europe and North America) and agricultural productivity was growing rapidly. A recurring theme of political–economic debate concerned the appropriate institutional arrangements for the development of trade and growth.

These issues are central to the work of Adam Smith (1723–1790). Smith was the first writer to systematise the argument for the importance of markets in allocating resources, although his emphasis was placed on what we would now call the dynamic effects of markets. His major work, *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776), contains the famous statement of the role of the 'invisible hand':

> But it is only for the sake of profit that any man employs a capital in the support of industry; and he will always, therefore, endeavour to employ it in the support of that industry of which the produce is likely to be of the greatest value, or to exchange for the greatest quantity, either of money or of other goods.
>
> As every individual, therefore, endeavours as much as he can both to employ his capital in the support of domestic industry, and so to direct that industry that its produce may be of the greatest value; every individual necessarily labours to render the annual revenue of the society as great as he can. He generally, indeed, neither intends to promote the public interest, nor knows how much he is promoting it . . . he is, in this as in many other cases, led by an invisible hand to promote an end which was no part of his intention . . .
>
> . . . By pursuing his own interest he frequently promotes that of society more effectively than when he really intends to promote it.
>
> *Smith ([1776] 1961), Book IV, Ch. 2, p. 477*

This belief in the efficacy of the market mechanism is a fundamental organising principle of the policy prescriptions of modern economics, including resource and environmental economics, as will be seen in our account of it in the rest of the book.

A central interest of the classical economists was the question of what determined standards of living and economic growth. Natural resources were seen as important determinants of national wealth and its growth. Land (sometimes used to refer to natural resources in general) was viewed as limited in its availability. When to this were added the assumptions that land was a necessary input to production and that it exhibited diminishing returns, the early classical economists came to the conclusion that economic progress would be a transient feature of history. They saw the inevitability of an eventual stationary state, in which the prospects for the living standard of the majority of people were bleak.

This thesis is most strongly associated with Thomas Malthus (1766–1834), who argued it most forcefully in his *Essay on the Principle of Population* (1798), giving rise to the practice of describing those who now question the feasibility of continuing long-run economic growth as 'neo-Malthusian'. For Malthus, a fixed land quantity, an assumed tendency for continual positive population growth, and diminishing returns in agriculture implied a tendency for output per capita to fall over time. There was, according to Malthus, a long-run tendency for the living standards of the mass of people to be driven down to a subsistence level. At the subsistence wage level, living standards would be such that the population could just reproduce itself, and the economy would attain a steady state with a constant population size and constant, subsistence-level, living standards.

This notion of a steady state was formalised and extended by David Ricardo (1772–1823), particularly in his *Principles of Political Economy and Taxation* (1817). Malthus's assumption of a fixed stock of land was replaced by a conception in which land was available in parcels of varying quality. Agricultural output could be expanded by increasing the intensive margin (exploiting a given parcel of land more intensively) or by increasing the extensive margin (bringing previously uncultivated land into productive use). However, in either case, returns to the land input were taken to be diminishing. Economic development then proceeds in such a way that the 'economic surplus' is appropriated increasingly in the form of rent, the return to land, and development again converges toward a Malthusian stationary state.

In the writings of John Stuart Mill (1806–1873) (see in particular Mill (1857)) one finds a full statement of classical economics at its culmination. Mill's work utilises the idea of diminishing returns, but recognises the countervailing influence of the growth of knowledge and technical progress in agriculture and in production more generally. Writing in Britain when output per person was apparently rising, not falling, he placed less emphasis on diminishing returns, reflecting the relaxation of the constraints of the extensive margin as colonial exploitation opened up new tranches of land, as fossil fuels were increasingly exploited, and as innovation rapidly increased agricultural productivity. The concept of a stationary state was not abandoned, but it was thought to be one in which a relatively high level of material prosperity would be attained.

Foreshadowing later developments in environmental economics, and the thinking of conservationists, Mill adopted a broader view of the roles played by natural resources than his predecessors. In addition to agricultural and extractive uses of land, Mill saw it as a source of amenity values (such as the intrinsic beauty of countryside) that would become of increasing relative importance as material conditions improved. We discuss a modern version of this idea in Chapter 11.

Mill's views are clearly revealed in the following extract from his major work.

> Those who do not accept the present very early stage of human improvement as its ultimate type may be excused for being comparatively indifferent to the kind of economic progress which excites the congratulations of ordinary politicians: the mere increase of production . . . It is only in the backward countries of the world that increased production is still an important object; in those most advanced, what is needed is a better distribution . . . There is room in the world, no doubt, and even in old countries, for a great increase in population, supposing the arts of life to go on improving, and capital to increase. But even if innocuous, I confess I see very little reason for desiring it. The density of population necessary to enable mankind to obtain, in the greatest degree, all of the advantages both of cooperation and of social intercourse, has, in all the most populous countries, been attained. A population may be too crowded, though all be amply supplied with food and raiment. It is not good for man to be kept perforce at all times in the presence of his species . . . Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature: with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture ploughed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub or flower could grow without being eradicated as a weed in the name of improved agriculture. If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increase of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not a happier or better population, I sincerely hope, for the sake of posterity, that they will be content to be stationary long before necessity compels them to it.
>
> *Mill (1857), Book IV*

It is worth noting explicitly that at the time that Mill wrote this the global population was less than one quarter of what it is now, and that average per capita income, as gross domestic product (GDP), in the then rich parts of the world was of the order of 10% of what it is now.[1] We briefly review some of the recent research on the determinants of self-assessed individual human happiness in Chapter 3.

1.2.2 Neoclassical economics: marginal theory and value

A series of major works published in the 1870s began the replacement of classical economics by what subsequently became known as 'neoclassical economics'. One outcome of this was a change in the manner in which value was explained. Classical economics saw value as arising from the labour power embodied (directly and indirectly) in output, a view which found its fullest embodiment in the work of Karl Marx. Neoclassical economists explained value as being determined in exchange, so reflecting preferences and costs of production. The concepts of price and value ceased to be distinct. Moreover, previous notions of absolute scarcity and value were replaced by a concept of relative scarcity, with relative values (prices) determined by the forces of supply and demand. This change in emphasis paved the way for the development of welfare economics, to be discussed shortly.

At the methodological level, the technique of marginal analysis was adopted, allowing earlier notions of diminishing returns to be given a formal basis in terms of diminishing marginal productivity in the context of an explicit production function. Jevons (1835–1882) and Menger (1840–1921) formalised the theory of consumer preferences in terms of utility and demand theory. The evolution of

[1] These statements are based on estimates in Table 2.1 in Maddison (2007). It gives world population as 1272 million in 1870 and 6279 million in 2003, and per capita GDP for Western Europe as 1960 1990$s in 1870 and 19 912 1990$s in 2003.

neoclassical economic analysis led to an emphasis on the structure of economic activity, and its allocative efficiency, rather than on the aggregate level of economic activity. Concern with the prospects for continuing economic growth receded, perhaps reflecting the apparent inevitability of growth in Western Europe at this time. Leon Walras (1834–1910) developed neoclassical General Equilibrium Theory, and in so doing provided a rigorous foundation for the concepts of efficiency and optimality that we employ extensively in this text. Alfred Marshall (1842–1924) (see *Principles of Economics*, 1890) was responsible for elaboration of the partial equilibrium supply-and-demand-based analysis of price determination so familiar to students of modern microeconomics. A substantial part of modern environmental economics continues to use these techniques as tools of exposition, as do we at many points throughout the book.

We remarked earlier that concern with the level (and the growth) of economic activity had been largely ignored in the period during which neoclassical economics was being developed. Economic depression in the industrialised economies in the inter-war years provided the backcloth against which John Maynard Keynes (1883–1946) developed his theory of income and output determination. The Keynesian agenda switched attention to aggregate supply and demand, and the reasons why market economies may fail to achieve aggregate levels of activity that involve the use of all of the available inputs to production. Keynes was concerned to explain, and provide remedies for, the problem of persistent high levels of unemployment, or recession.

This direction of development in mainstream economics had little direct impact on the emergence of resource and environmental economics. However, Keynesian 'macroeconomics', as opposed to the microeconomics of neoclassical economics, was of indirect importance in stimulating a resurgence of interest in growth theory in the middle of the twentieth century, and the development of a neoclassical theory of economic growth. What is noticeable in early neoclassical growth models is the absence of land, or any natural resources, from the production function used in such models. Classical limits-to-growth arguments, based on a fixed land input, did not have any place in early neoclassical growth modelling.

The introduction of natural resources into neoclassical models of economic growth occurred in the 1970s, when some neoclassical economists first systematically investigated the efficient and optimal depletion of resources. This body of work, and the developments that have followed from it, is natural resource economics. The models of efficient and optimal exploitation of natural resources that we present and discuss in Chapters 14, 15, 17 and 18 are based on the writings of those authors. We will also have call to look at such models in Chapter 19, where we discuss the theory of accounting for the environment as it relates to the question of sustainability.

1.2.3 Welfare economics

The final development in mainstream economic theory that needs to be briefly addressed here is the development of a rigorous theory of welfare economics. Welfare economics, as you will see in Chapter 4, attempts to provide a framework in which normative judgements can be made about alternative configurations of economic activity. In particular, it attempts to identify circumstances under which it can be claimed that one allocation of resources is better (in some sense) than another.

Not surprisingly, it turns out to be the case that such rankings are only possible if one is prepared to accept some ethical criterion. The most commonly used ethical criterion adopted by classical and neoclassical economists derives from the utilitarian moral philosophy, developed by David Hume, Jeremy Bentham and John Stuart Mill. We explore this ethical structure in Chapter 3. Suffice to say now that utilitarianism has social welfare consisting of some weighted average of the total utility levels enjoyed by all individuals in the society.

Economists have attempted to find a method of ranking different states of the world which does not require the use of a social welfare function, and makes little use of ethical principles, but is nevertheless useful in making prescriptions about resource allocation. The notion of economic efficiency, also known as allocative efficiency or Pareto optimality (because it was developed by Vilfredo Pareto (1897)), is what they have come up with. These ideas are examined at length in Chapter 4. It can be shown that, given certain rather stringent conditions, an economy organised as a competitive market economy will attain a state of economic efficiency. This is the modern, and rigorous, version of Adam Smith's story about the benign influence of the invisible hand.

Where the conditions do not hold, markets do not attain efficiency in allocation, and a state of 'market failure' is said to exist. One manifestation of market failure is the phenomenon of 'externalities'. These are situations where, because of the structure of property rights, relationships between economic agents are not all mediated through markets. Market failure and the means for its correction will be discussed in Chapter 4.

The problem of pollution is a major concern of environmental economics. It first attracted the attention of economists as a particular example of the general class of externalities. Important early work in the analysis of externalities and market failure is to be found in Marshall (1890). The first systematic analysis of pollution as an externality is to be found in Pigou (1920). However, environmental economics did not really 'take off' until the 1970s. The modern economic treatment of problems of environmental pollution is covered in Chapters 5, 6 and 7, and in Chapter 16.

Environmental economics is also concerned with the natural environment as a source of recreational and amenity services, which is what Mill was drawing attention to in the quotation above. This role for the environment can be analysed using concepts and methods similar to those used in looking at pollution problems. This branch of modern environmental economics is covered in Chapters 11, 12 and 13. Like pollution economics, it makes extensive use of the technique of cost–benefit analysis, which emerged in the 1950s and 1960s as a practical vehicle for applied welfare economics and policy advice. The basic structure and methodology of cost–benefit analysis is dealt with in Chapter 11, building on the discussion of market failure and public policy in Chapter 4.

The modern sub-disciplines of natural resource economics and environmental economics have largely distinct roots in the core of modern mainstream economics. The former emerged mainly out of neoclassical growth economics, the latter out of welfare economics and the study of market failure. Both can be said to date effectively from the early 1970s, though of course earlier contributions can be identified.

1.2.4 Ecological economics

Ecological economics is a relatively new, interdisciplinary, field. In the 1980s a number of economists and natural scientists came to the conclusion that if progress was to be made in understanding and addressing environmental problems it was necessary to study them in an interdisciplinary way. The International Society for Ecological Economics was set up in 1989. The precise choice of name for this society may have been influenced by the fact that a majority of the natural scientists involved were ecologists, but more important was the fact that economics and ecology were seen as the two disciplines most directly concerned with what was seen as the central problem – sustainability.

Ecology is the study of the distribution and abundance of animals and plants. A central focus is an ecosystem, which is an interacting set of plant and animal populations and their abiotic, non-living, environment. The Greek word 'oikos' is the common root for the 'eco' in both economics and ecology. Oikos means 'household', and it could be said that ecology is the study of nature's housekeeping, while economics is the study of human housekeeping. Ecological economics could then be said to be the study of how these two sets of housekeeping are related to one another. Earlier in this chapter we said that sustainability involves taking care of posterity. Most of those who would wish to be known as ecological economists are concerned that the scale of human housekeeping is now such that it threatens the viability of nature's housekeeping in ways which will adversely affect future generations of humans.

The distinguishing characteristic of ecological economics is that it takes as its starting point and its central organising principle the fact that the economic system is part of the larger system that is planet earth. It starts from the recognition that the economic and environmental systems are interdependent, and studies the joint economy–environment system in the light of principles from the natural sciences, particularly thermodynamics and ecology. We shall briefly discuss these matters in the next chapter, which has the title 'The origins of the sustainability problem', as it is the interdependence of economic and natural systems that gives rise to the sustainability problem.

Kenneth Boulding is widely regarded as one of the 'founding fathers' of ecological economics. Box 1.1 summarises a paper that he wrote in 1966 which uses vivid metaphors to indicate the change in ways of thinking that he saw as necessary, given the laws of nature and their implications for economic activity. As we have seen, the dependence of economic activity on its material base – the natural environment – was a central concern of classical economics, but not of neoclassical economics. Boulding was one of a few scholars, including some economists, who continued, during the ascendancy of neoclassical economics, to insist on the central importance of studying economics in a way which takes on board what is known about the laws of nature as they affect the material basis for economic activity. As is made clear in Box 1.1, Boulding did not, and ecological economics does not, take the view that everything that resource and environmental economics has to say, for example, about using price incentives to deal with environmental problems is wrong. Rather, the point is that what it has to say needs to be put in the proper context, one where the economic system is seen as a subsystem of a larger system.

Box 1.1 Economics of 'Spaceship Earth'

In a classic paper written in 1966, 'The economics of the coming Spaceship Earth', Kenneth Boulding discusses a change in orientation that is required if mankind is to achieve a perpetually sustainable economy. He begins by describing the prevailing image which man has of himself and his environment. The 'cowboy economy' describes a state of affairs in which the typical perception of the natural environment is that of a virtually limitless plain, on which a frontier exists that can be pushed back indefinitely. This economy is an open system, involved in interchanges with the world outside. It can draw upon inputs from the outside environment, and send outputs (in the form of waste residuals and so on) to the outside. In the cowboy economy perception, no limits exist on the capacity of the outside to supply or receive energy and material flows.

Boulding points out that, in such an economy, the measures of economic success are defined in terms of flows of materials being processed or transformed. Roughly speaking, income measures such as GDP or GNP reflect the magnitudes of these flows – the cowboy perception regards it as desirable that these flows should be as large as possible.

However, Boulding argues, this economy is built around a flawed understanding of what is physically possible in the long run. A change in our perception is therefore required to one in which the earth is recognised as being a closed system or, more precisely, a system closed in all but one respect – energy inputs are received from the outside (such as solar energy flows) and energy can be lost to the outside (through radiative flows, for example). In material terms, though, planet earth is a closed system: matter cannot be created or destroyed, and the residuals from extraction, production and consumption activities will always remain with us, in one form or another.

Boulding refers to this revised perception as that of the 'spaceman economy'. Here, the earth is viewed as a single spaceship, without unlimited reserves of anything. Beyond the frontier of the spaceship itself, there exist no reserves from which the spaceship's inhabitants can draw resources nor sinks into which they can dispose of unwanted residuals. On the contrary, the spaceship is a closed material system, and energy inputs from the outside are limited to those perpetual but limited flows that can be harnessed from the outside, such as solar radiation.

Within this spaceship, if mankind is to survive indefinitely, man must find his place in a perpetually reproduced ecological cycle. Materials usage is limited to that which can be recycled in each time period; that, in turn, is limited by the quantity of solar and other external energy flows received by the spaceship.

Box 1.1 ***continued***

What is an appropriate measure of economic performance in spaceship earth? It is not the magnitude of material flows, as measured by GNP or the like. On the contrary, it is desirable that the spaceship maintain such flows of material and energy throughput at low levels. Instead, the well-being of the spaceship is best measured by the state – in terms of quality and quantity – of its capital stock, including the state of human minds and bodies.

So, for Boulding, a 'good' state to be in is one in which certain stocks are at high levels – the stock of knowledge, the state of human health, and the stock of capital capable of yielding human satisfaction. Ideally we should aim to make material and energy flows as small as possible to achieve any chosen level of the spaceship's capital stock, maintained over indefinite time.

Boulding is, of course, arguing for a change in our perceptions of the nature of economy–environment interactions, and of what it is that constitutes economic success. He states that

> The shadow of the future spaceship, indeed, is already falling over our spendthrift merriment. Oddly enough, it seems to be in pollution rather than exhaustion, that the problem is first becoming salient. Los Angeles has run out of air, Lake Erie has become a cesspool, the oceans are getting full of lead and DDT, and the atmosphere may become man's major problem in another generation, at the rate at which we are filling it up with junk.

Boulding concludes his paper by considering the extent to which the price mechanism, used in a way to put prices on external diseconomies, can deal with the transition to spaceship earth. He accepts the need for market-based incentive schemes to correct such diseconomies, but argues that these instruments can only deal with a small proportion of the matters which he raises. Boulding concludes:

> The problems which I have been raising in this paper are of larger scale and perhaps much harder to solve . . . One can hope, therefore, that as a succession of mounting crises, especially in pollution, arouse public opinion and mobilize support for the solution of the immediate problems, a learning process will be set in motion which will eventually lead to an appreciation of and perhaps solutions for the larger ones.

Source: Boulding (1966)

To date, the impact of ecological economics on the approach to the natural environment that emerged from mainstream economics has been somewhat limited, and this book will largely reflect that. We will be dealing mainly with mainstream resource and environmental economics, though the next two chapters do address the problem of sustainability. While the theme of sustainability runs through the book, it is not obviously at the forefront in Chapters 4 to 18 which are, mainly, about the mainstream approach. We do, however, at some points in those chapters briefly consider how adopting an ecological economics perspective would affect analysis and policy. In the final chapter of the book, Chapter 19, sustainability returns to the forefront in the context of a discussion of the prospects for promoting it by better economic accounting.

1.3 Fundamental issues in the economic approach to resource and environmental issues

Here we provide a brief anticipatory sketch of four features of the economic approach to resource and environmental issues that will be covered in this book.

1.3.1 Property rights, efficiency and government intervention

We have already stated that a central question in resource and environmental economics concerns allocative efficiency. The role of markets and prices is central to the analysis of this question. As we have noted, a central idea in modern economics is that, given the necessary conditions, markets will bring about efficiency in allocation. Well-defined and enforceable private property rights are one of the necessary conditions. Because property rights do not exist, or are not clearly defined, for many environmental resources, markets fail to allocate those resources efficiently. In such circumstances, price signals fail to reflect true social costs and benefits, and a prima facie case exists for government policy intervention to seek efficiency gains.

Deciding where a case for intervention exists, and what form it should take, is central in all of resource and environmental economics, as we shall see throughout the rest of this book. The foundations for the economic approach to policy analysis are set out in Chapter 4, and the approach is applied in the subsequent chapters. Some environmental problems cross the boundaries of nation states and are properly treated as global problems. In such cases there is no global government with the authority to act on the problem in the same way as the government of a nation state might be expected to deal with a problem within its borders. The special features of international environmental problems are considered in Chapter 9.

1.3.2 The role, and the limits, of valuation, in achieving efficiency

As just observed, many environmental resources – or the services yielded by those resources – do not have well-defined property rights. Clean air is one example of such a resource. Such resources are used, but without being traded through markets, and so will not have market prices. A special case of this general situation is external effects, or externalities. As discussed in Chapter 4, an externality exists where a consumption or production activity has unintended effects on others for which no compensation is paid. Here, the external effect is an untraded – and unpriced – product arising because the victim has no property rights that can be exploited to obtain compensation for the external effect. Sulphur emissions from a coal-burning power station might be an example of this kind of effect.

However, the absence of a price for a resource or an external effect does not mean that it has no value. Clearly, if well-being is affected, there is a value that is either positive or negative depending on whether well-being is increased or decreased. In order to make allocatively efficient decisions, these values need to be estimated in some way. Returning to the power station example, government might wish to impose a tax on sulphur emissions so that the polluters pay for their environmental damage and, hence, reduce the amount of it to the level that goes with allocative efficiency. But this cannot be done unless the proper value can be put on the otherwise unpriced emissions.

There are various ways of doing this – collectively called valuation techniques – which will be explored at some length in Chapter 12. Such techniques are somewhat controversial. There is disagreement between economists over the extent to which the techniques can be expected to produce accurate valuations for unpriced environmental services. These are discussed in Chapter 12. Many non-economists with an interest in how social decisions that affect the environment are made raise rather more fundamental problems about the techniques and their use. Their objection is not, or at least not just, that the techniques may provide the wrong valuations. Rather, they claim that making decisions about environmental services on the basis of monetary valuations of those services is simply the wrong way for society to make such decisions. These objections, and some alternative ways proposed for society to make decisions about the environment, are considered in Chapter 11.

1.3.3 The time dimension of economic decisions

Natural resource stocks can be classified in various ways. A useful first cut is to distinguish between ‘stock’ and ‘flow’ resources. Whereas stock resources, plant and animal populations and mineral deposits, have the characteristic that today’s use has implications for tomorrow’s availability, this is not the case with flow resources. Examples of flow resource are solar radiation, and the power of the wind, of tides and of flowing water. Using more solar radiation today does not itself have any implications for the availability of solar radiation tomorrow. In the case of stock resources, the level of use today does have implications for availability tomorrow.

Within the stock resources category there is an important distinction between 'renewable' and 'non-renewable' resources. Renewable resources are biotic, plant and animal populations, and have the capacity to grow in size over time, through biological reproduction. Non-renewable resources are abiotic, stocks of minerals, and do not have that capacity to grow over time. What are here called non-renewable resources are sometimes referred to as 'exhaustible', or 'depletable', resources. This is because there is no positive constant rate of use that can be sustained indefinitely – eventually the resource stock must be exhausted. This is not actually a useful terminology. Renewable resources are exhaustible if harvested for too long at a rate exceeding their regeneration capacities.

From an economic perspective, stock resources are assets yielding flows of environmental services over time. In considering the efficiency and optimality of their use, we must take account not only of use at a point in time but also of the pattern of use over time. Efficiency and optimality have, that is, an intertemporal, or dynamic, dimension, as well as an intratemporal, or static, dimension. Chapter 11 sets out the basics of intertemporal welfare economics. In thinking about the intertemporal dimension of the use of environmental resources, attention must be given to the productiveness of the capital that is accumulated as a result of saving and investment. If, by means of saving and investment, consumption is deferred to a later period, the increment to future consumption that follows from such investment will generally exceed the initial consumption quantity foregone. The size of the pay-off to deferred consumption is reflected in the rate of return to investment.

Environmental resource stocks similarly have rates of return associated with their deferred use. The relations between rates of return to capital as normally understood in economics and the rates of return on environmental assets must be taken into account in trying to identify efficient and optimal paths of environmental resource use over time. The arising theory of the efficient and optimal use of natural and environmental resources over time is examined in Chapters 14, 15, 17 and 18, and is drawn on in Chapter 19. As discussed in Chapter 16, many pollution problems also have an intertemporal dimension, and it turns out that the analysis developed for thinking about the intertemporal problems of resource use can be used to analyse those problems.

1.3.4 Substitutability and irreversibility

Substitutability and irreversibility are important, and related, issues in thinking about policy in relation to the natural environment. If the depletion of a resource stock is irreversible, and there is no close substitute for the services that it provides, then clearly the rate at which the resource is depleted has major implications for sustainability. To the extent that depletion is not irreversible and close substitutes exist, there is less cause for concern about the rate at which the resource is used.

There are two main dimensions to substitutability issues. First, there is the question of the extent to which one natural resource can be replaced by another. Can, for example, solar power substitute for the fossil fuels on a large scale? This is, as we shall see, an especially important question given that the combustion of fossil fuels not only involves the depletion of non-renewable resources, but also is a source of some major environmental pollution problems, such as the so-called greenhouse effect which entails the prospect of global climate change, as discussed in Chapter 9.

Second, there is the question of the degree to which an environmental resource can be replaced by other inputs, especially the human-made capital resulting from saving and investment. As we shall see, in Chapters 3, 14 and 19, this question is of particular significance when we address questions concerning long-run economy–environment interactions, and the problem of sustainability.

Human-made capital is sometimes referred to as reproducible capital, identifying an important difference between stocks of it and stocks of non-renewable resources. The latter are not reproducible, and their exploitation is irreversible in a way that the use of human-made capital is not. We shall discuss this further in the next chapter, and some arising implications in later chapters, especially 14 and 19. With renewable resource stocks, depletion is reversible to the extent that harvesting is at rates that allow regeneration. Some of the implications are discussed in Chapter 17. Some pollution problems may involve irreversible effects, and the extinction of a species of plant or animal is certainly irreversible.

Some assemblages of environmental resources are of interest for the amenity services, recreation and aesthetic enjoyment that they provide, as well as for their potential use as inputs to production. A wilderness area, for example, could be conserved as a national park or developed for mining. Some would also argue that there are no close substitutes for the services of wilderness. A decision to develop such an area would be effectively irreversible, whereas a decision to conserve would be reversible. We show in Chapter 13 that under plausible conditions this asymmetry implies a stronger preference for non-development than would be the case where all decisions are reversible, and that this is strengthened when it is recognised that the future is not known with certainty. Imperfect knowledge of the future is, of course, the general condition, but it is especially relevant to decision making about many environmental problems, and has implications for how we think about making such decisions.

1.4 Reader's guide

We have already noted in which chapters various topics are covered. Now we will briefly set out the structure of this text, and explain the motivation for that structure.

In Part I we deal with 'Foundations' of two kinds. First, in Chapter 2, we explain why many people think that there is a sustainability problem. We consider the interdependence of the economy and the environment, look at the current state of human development, and at some views on future prospects. Second, in the next two chapters, we work through the conceptual basis and the analytical tools with which economists approach environmental problems. Chapter 3 looks at the ethical basis for policy analysis in economics. Chapter 4 is about welfare economics and markets – what they achieve when they work properly, why they do not always work properly, and what can be done about it when they do not work properly.

Throughout the book we have put as much of the mathematics as is possible in appendices, of which extensive use is made. These appendices will be found on the companion website for this book: www.pearsoned.co.uk/perman. Readers who have learned the essentials of the calculus of constrained optimisation will have no problems with the mathematics used in the appendices in Part I. Appendix 3.1 provides a brief account of the mathematics of constrained optimisation. The arguments of Part I can be followed without using the mathematics in the appendices, but readers who work through them will obtain a deeper understanding of the arguments and their foundations.

Part II is about 'Environmental pollution'. It turns out that much, but not all, of what economists have to say about pollution problems relates to the question of intratemporal allocative efficiency and does not essentially involve a time dimension. The static analysis of pollution problems is the focus of Part II. Static, as opposed to dynamic, analysis follows naturally from the material covered most intensively in Chapter 4, and, subject to an exception to be noted shortly, the mathematics used in the appendices in Part II is of the same kind as used in the appendices in Part I.

Chapter 5 considers the setting of targets for pollution control, and Chapter 6 looks at the analysis of the policy instruments that could be used to meet those targets. In these chapters it is assumed that the government agency responsible for pollution control has complete information about all aspects of the pollution problem to be addressed. This is a patently unrealistic assumption, and Chapter 7 examines the consequences of its relaxation. The analysis in these three chapters is partial, analysing the control of a particular pollutant as if it were the only such problem, and as if what were done about it had no implications for the rest of the economy. Chapter 8, in contrast, takes an approach which looks at the economy as a whole, using input–output analysis and introducing applied general equilibrium modelling. This chapter includes an appendix that provides a brief review of the matrix algebra which facilitates the understanding and application of these methods. Part II finishes with Chapters 9 and 10, which deal, respectively, with environmental problems that cross national frontiers, and with how thinking about international trade is affected by the existence of environmental problems.

Part III has the title ‘Project appraisal’. Its focus is on the rationale for, and application of, the methods and techniques that economists have developed for evaluating whether going ahead with some discrete investment project, or policy innovation, is in the public interest. Of particular concern here, of course, are projects and policies with environmental impacts. Also, the focus is on projects and policies which have consequences stretching out over time. Chapter 11 deals with the principles of intertemporal welfare economics and their application in cost–benefit analysis. Chapter 11 also looks at some alternative methods for project appraisal that have been advocated, especially by those who have ethical objections to the use of cost–benefit analysis where the natural environment is involved. A necessary input to a cost–benefit analysis of a project with effects on the natural environment is a monetary evaluation of those effects. The methods that economists have devised for monetary evaluation of non-marketed environmental services are explained in Chapter 12. Chapter 13 looks at the implications for project appraisal of recognition of the facts that when looking at projects with environmental impacts, we are often dealing with impacts that are irreversible, and always considering future effects about which our knowledge is incomplete.

In Part III the arguments and analysis are developed mainly in the context of the recreation and amenity services that the natural environment provides, though they are, of course, also relevant to the problem of environmental pollution, the focus of Part II. In Part IV we turn to a focus on the issues associated with the extraction of natural resources from the environment for use as inputs to production. The problems that have most interested economists here are essentially dynamic in nature, that is, are problems in intertemporal allocation. In addressing these problems, economists typically use the mathematics of ‘optimal control’. We have minimised the explicit use of this mathematics in the body of the text, but we do make extensive use of it in the appendices in Part IV. For readers not familiar with this sort of mathematics, Appendix 14.1 provides a brief account of it, treating it as an extension of the ideas involved in ordinary constrained optimisation developed in Appendix 3.1.

Chapter 14 introduces the application of the basic ideas about intertemporal optimality and efficiency, developed in Chapter 11, to the question of natural resource extraction. Chapter 15 looks specifically at the extraction of non-renewable resources, that is, stocks of minerals and fossil fuels. The case of renewable resources – populations of plants and animals harvested for use in production and consumption – is dealt with in Chapter 17. Trees are plants with some special characteristics, and Chapter 18 reviews the major elements of forestry economics. Many important pollution problems have the characteristic that the pollutant involved accumulates in the environment as a stock, which may decay naturally over time. Analysis of such pollution problems has much in common with the analysis of natural resource extraction, and is dealt with in Chapter 16. Finally in Part IV we return to the sustainability issue. Chapter 19 is about modifying standard accounting procedures so as to have economic performance indicators reflect environmental impacts, and particularly so as to measure sustainable national income.

Summary

There is not a single methodology used by all economists working on matters related to natural resources and the environment. Ecological economists have argued the need to work towards a more holistic discipline that would integrate natural-scientific and economic paradigms. Some ecological economists argue further that the sustainability problem requires nothing less than a fundamental change in social values, as well as a scientific reorientation. While some movement has been made in the direction of interdisciplinary cooperation, most analysis is still some way from having achieved integration. At the other end of a spectrum of methodologies are economists who see no need to go beyond the application of neoclassical techniques to environmental problems, and stress the importance of constructing a more complete set of quasi-market incentives to induce efficient behaviour. Such economists would reject the idea that existing social values need to be questioned, and many have great faith in the ability of continuing technical progress to ameliorate problems of resource scarcity and promote sustainability. Ecological economists tend to be more sceptical about the extent to which technical progress can overcome the problems that follow from the interdependence of economic and environmental systems.

However, there is a lot of common ground between economists working in the area, and it is this that we mainly focus upon in this text. Nobody who has seriously studied the issues believes that the economy's relationship to the natural environment can be left entirely to market forces. Hardly anybody now argues that market-like incentives have no role to play in that relationship. In terms of policy, the arguments are about how much governments need to do, and the relative effectiveness of different kinds of policy instruments. Our aim in this book is to work through the economic analysis relevant to these kinds of questions, and to provide information on the resource and environmental problems that they arise from. We begin, in the next chapter, by discussing the general interdependence of the economic and environmental systems, and the concerns about sustainability that this has given rise to.

Further reading

As all save one of the topics and issues discussed in this chapter will be dealt with more comprehensively in subsequent chapters, we shall not make any suggestions for further reading here other than for that one topic – the history of economics. Blaug (1985), *Economic Theory in Retrospect*, is essential reading for anybody who wants to study the history of economic ideas in detail. For those who do not require a comprehensive treatment, useful alternatives are Barber (1967) and Heilbronner (1991). Crocker (1999) is a short overview of the history of environmental and resource economics, providing references to seminal contributions.

The leading specialist journals, in order of date of first issue, are: *Land Economics*, *Journal of Environmental Economics and Management*, *Ecological Economics*, *Environmental and Resource Economics*, *Environment and Development Economics*. The first issue of *Ecological Economics*, February 1989, contains several articles on the nature of ecological economics. The May 2000 issue, Vol. 39, number 3, of the *Journal of Environmental Economics and Management* marks the journal's 25th anniversary and contains articles reviewing the major developments in environmental and resource economics over its lifetime.

The *Journal of Environmental Economics and Management* is run by the Association of Environmental and Resource Economists, whose website at www.aere.org has useful information and links. The equivalent European association is the European Association of Environmental and Resource Economists – www.vwl.unimannheim.de/conrad/eaere/ – which runs the journal *Environmental and Resource Economics*. The address for the website of the International Society for Ecological Economics is www.ecoeco.org/.

CHAPTER 2 The origins of the sustainability problem

The global challenge can be simply stated: To reach sustainability, humanity must increase the consumption levels of the world's poor, while at the same time reducing humanity's ecological footprint

Meadows *et al.* (2005), p. xv

Learning objectives

In this chapter you will

- learn how economic activity depends upon and affects the natural environment
- be introduced to some basic material from the environmental sciences
- learn about the proximate drivers of the economy's impact on the environment – population, affluence and technology
- review the current state of human economic development
- consider the argument that the environment sets limits to economic growth
- learn about the emergence of the idea of sustainable development

Introduction

We inhabit a world in which the human population has risen dramatically over the past century and may almost double during the next. The material demands being made by the average individual have been increasing rapidly, though many human beings now alive are desperately poor. Since the 1950s and 1960s economic growth has been generally seen as *the* solution to the problem of poverty. Without economic growth, poverty alleviation involves redistribution from the better-off to the poor, which encounters resistance from the better-off. In any case, there may be so many poor in relation to the size of the better-off group that the redistributive solution to the problem of poverty is simply impossible – the cake is not big enough to provide for all, however thinly the slices are cut. Economic growth increases the size of the cake. With enough of it, it may be possible to give everybody at least a decent slice, without having to reduce the size of the larger slices.

However, the world's resource base is limited, and contains a complex, and interrelated, set of ecosystems that are currently exhibiting signs of fragility. It is increasingly questioned whether the global economic system can continue to grow without undermining the natural systems which are its ultimate foundation.

This set of issues we call 'the sustainability problem' – how to alleviate poverty in ways that do not affect the natural environment such that future economic prospects suffer. In this chapter we set out the basis for the belief that such a problem exists.

This chapter is organised as follows. We first look at the interdependence of the economy and the environment, and give a brief overview of some environmental science basics that are relevant to this. In the second section the proximate drivers of the economy's impact on the environment are considered. The third section of the chapter presents data on the current state of human development in relation to the problems of poverty and inequality. In this section we note the attachment of economists to economic growth as the solution to the poverty problem. In the next section we consider limits to growth. The chapter ends by looking at the emergence in the 1980s of the idea of sustainable development – growth that does not damage the environment – and progress towards its realisation.

2.1 Economy–environment interdependence

Economic activity takes place within, and is part of, the system which is the earth and its atmosphere. This system we call 'the natural environment', or more briefly 'the environment'. This system itself has an environment, which is the rest of the universe. Figure 2.1 is a schematic representation of the two-way relationships between, the interdependence of, the economy and the environment.[1]

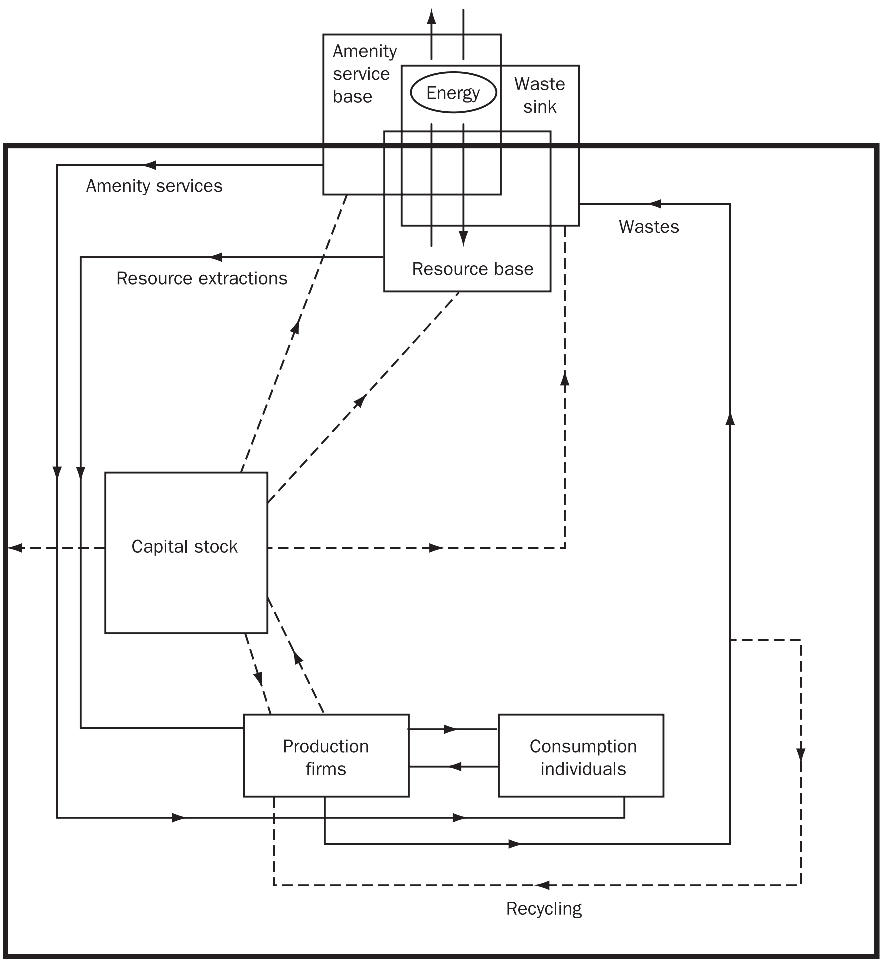

Figure 2.1 Economic activity in the natural environment

[1] Figure 2.1 is taken from Common (1995), where economy–environment interdependence is discussed at greater length than here. References to works which deal more fully, and rigorously, with the natural science matters briefly reviewed here are provided in the Further Reading section at the end of the chapter.

The outer heavy black lined box represents the environment, which is a thermodynamically closed system, in that it exchanges energy but not matter with its environment. The environment receives inputs of solar radiation. Some of that radiation is absorbed and drives environmental processes. Some is reflected back into space. This is represented by the arrows crossing the heavy black line at the top of the figure. Matter does not cross the heavy black line. The balance between energy absorption and reflection determines the way the global climate system functions. The energy in and out arrows are shown passing through three boxes, which represent three of the functions that the environment performs in relation to economic activity. The fourth function, represented by the heavy black lined box itself, is the provision of the life-support services and those services which hold the whole functioning system together. Note that the three boxes intersect one with another and that the heavy black line passes through them. This is to indicate that the four functions interact with one another, as discussed below.

Figure 2.1 shows economic activity located within the environment and involving production and consumption, both of which draw upon environmental services, as shown by the solid lines inside the heavy lined box. Not all of production is consumed. Some of the output from production is added to the human-made, reproducible, capital stock, the services of which are used, together with labour services, in production. Figure 2.1 shows production using a third type of input, resources extracted from the environment. Production gives rise to wastes inserted into the environment. So does consumption. Consumption also uses directly a flow of amenity services from the environment to individuals without the intermediation of productive activity.

We now discuss these four environmental functions, and the interactions between them, in more detail.

2.1.1 The services that the environment provides

As noted in the previous chapter, natural resources used in production are of several types. One distinguishing characteristic is whether the resource exists as a stock or a flow. The difference lies in whether the level of current use affects future availability. In the case of flow resources there is no link between current use and future availability. The prime example of a flow resource is solar radiation – if a roof has a solar water heater on it, the amount of water heating done today has no implications for the amount that can be done tomorrow. Wave and wind power are also flow resources. Stock resources are defined by the fact that the level of current use does affect future availability.

Within the class of stock resources, a second standard distinction concerns the nature of the link between current use and future availability. Renewable resources are biotic populations – flora and fauna. Non-renewable resources are minerals, including the fossil fuels. In the former case, the stock existing at a point in time has the potential to grow by means of natural reproduction. If in any period use of the resource is less than natural growth, stock size grows. If use, or harvest, is always the same as natural growth, the resource can be used indefinitely. Such a harvest rate is often referred to as a 'sustainable yield'. Harvest rates in excess of sustainable yield imply declining stock size. For non-renewable resources there is no natural reproduction, except on geological timescales. Consequently, more use now necessarily implies less future use.

Within the class of non-renewables the distinction between fossil fuels and the other minerals is important. First, the use of fossil fuels is pervasive in industrial economies, and could be said to be one of their essential distinguishing characteristics. Second, fossil fuel combustion is an irreversible process in that there is no way in which the input fuel can be even partially recovered after combustion. In so far as coal, oil and gas are used to produce heat, rather than as inputs to chemical processes, they cannot be recycled. Minerals used as inputs to production can be recycled. This means that whereas in the case of minerals there exists the possibility of delaying, for a given use rate, the date of exhaustion of a given initial stock, in the case of fossil fuels there does not. Third, fossil fuel combustion is a major source of a number of waste emissions, especially into the atmosphere. One such emission is carbon dioxide, CO_2, the most important of the greenhouse gases which are driving climate change.

Many of the activities involved in production and consumption give rise to waste products, or residuals, to be discharged into the natural environment. Indeed, as we shall see when we discuss the materials balance principle, such insertions into the environment are the necessary corollary of the extraction of material resources from it. In economics, questions relating to the consequences of waste discharge into the environment are generally discussed under the heading of 'pollution'. To the extent, and only to the extent, that waste discharge gives rise to problems perceived by humans, economists say that there is a pollution problem. Pollution problems can be conceptualised in two ways. One, which finds favour with economists, sees pollution as a stock of material resident in the natural environment. The other, which finds favour more with ecologists, sees pollution as a flow which affects the natural environment.

In the former case, pollution is treated in the same way as a stock resource, save that the stock has negative value. Residual flows into the environment add to the stock; natural decay processes subtract from it. We will look at pollution modelled this way in Chapter 16. The flow model treats the environment as having an 'assimilative capacity', defined in terms of a rate of residual flow. Pollution is then the result of a residual flow rate in excess of assimilative capacity. There is no pollution if the residual flow rate is equal to, or less than, assimilative capacity. If the residual flow rate is persistently in excess of assimilative capacity, the latter declines over time, and may eventually go to zero.

In Figure 2.1 amenity services flow directly from the environment to individuals. The biosphere provides humans with recreational facilities and other sources of pleasure and stimulation. Swimming from an ocean beach does not require productive activity to transform an environmental resource into a source of human satisfaction, for example. Wilderness recreation is defined by the absence of other human activity. Some people like simply lying out of doors in sunshine. The role of the natural environment in regard to amenity services can be appreciated by imagining its absence, as would be the case for the occupants of a space vehicle. In many cases the flow to individuals of amenity services does not directly involve any consumptive material flow. Wilderness recreation, for example, is not primarily about consuming resources in the wilderness area, though it may involve this in the use of wood for fires, the capture of game for food and so on. A day on the beach does not involve any consumption of the beach in the way that the use of oil involves its consumption. This is not to say that flows of amenity services never impact physically on the natural environment. Excessive use of a beach area can lead to changes in its character, as with the erosion of sand dunes following vegetation loss caused by human visitation.

The fourth environmental function, shown in Figure 2.1 as the heavy box, is difficult to represent in a simple and concise way. Over and above serving as resource base, waste sink and amenity base, the biosphere currently provides the basic life-support functions for humans. While the range of environmental conditions that humans are biologically equipped to cope with is greater than for most other species, there are limits to the tolerable. We have, for example, quite specific requirements in terms of breathable air. The range of temperatures that we can exist in is wide in relation to conditions on earth, but narrow in relation to the range on other planets in the solar system. Humans have minimum requirements for water input. And so on. The environment functions now in such a manner that humans can exist in it. An example will illustrate what is involved.

Consider solar radiation. It is one element of the resource base, and for some people sunbathing is an environmental amenity service. In fact, solar radiation as it arrives at the earth's atmosphere is harmful to humans. There it includes the ultraviolet wavelength UV-B, which causes skin cancer, adversely affects the immune system and can cause eye cataracts. UV-B radiation affects other living things as well. Very small organisms are likely to be particularly affected, as UV-B can penetrate only a few layers of cells. This could be a serious problem for marine systems, where the base of the food chain consists of very small organisms living in the surface layers of the ocean, which UV-B reaches. UV-B radiation also affects photosynthesis in green plants adversely.

Solar radiation arriving at the surface of the earth has much less UV-B than it does arriving at