An Introduction to Sustainable Resource Use
An Introduction to Sustainable Resource Use

Callum Hill
## Contents

Foreword vi
List of figures and tables viii
List of abbreviations xi

1 Background (crisis? what crisis?) 1
2 Thermodynamics (the science of energy and change) 17
3 Resources (how much is left?) 43
4 Consumption (if we all get richer is this good for the planet?) 71
5 Impacts (the consequences of resource use) 91
6 Ecologic (integrating industry with nature) 117
7 Feedstocks (how can plants supply our technical needs?) 135
8 Forestry (criminal or saviour?) 157
9 Conclusions (the end or the beginning?) 183

References 205

Appendix 215
Index 217
Foreword

Humankind’s stress on the regional natural resources required for survival has impacted civilizations for centuries, if not millennia. Empires have risen and fallen over control of critical resources. Industrialization has greatly accelerated and globalized these impacts in the last two centuries. No longer does the world have the time or luxury to permit one region’s natural resources to recover while another’s is plundered. With this globalization has come increased visibility and public awareness of the damage being done. The issues surrounding the sustainable use of resources came to dominate public discourse during the second half of the 20th century. These issues will only increase in importance in the 21st century as people increasingly ask, ‘Will we be able to live sustainably on the planet this century, or ever?’ However, the path to sustainable use of global resources is not an easy one and there are many blind alleys and pitfalls for the unwary.

An Introduction to Sustainable Resource Use examines the consequences of the way we use materials today and clearly demonstrates that there are no simple answers. The linear throughput model of material use arises from the early days of the industrial revolution when resources seemed inexhaustible and there was little concern expressed for the environment. In recent years we have become more aware of the finite nature of the planetary resources and the ability of the environment to be able to cope with our wastes. Scientists have voiced many warnings in the past. However, as Callum Hill points out in this extremely valuable and interesting text, many dire projections have proved to be overly pessimistic or just plain wrong. But there are limits, and his writings help the reader understand what those limits are and how we might more realistically view sustainable existence.

Human beings have proven to be amply capable of exploiting natural resource supplies while ignoring the finite nature of those resources, thus leading to a misplaced sense of security. Perhaps less well understood, and an issue that Callum Hill thoroughly examines, is that the more pressing limits that we currently face are actually found at the other end of the ‘pipe’ (i.e. the ability of the planet to deal with the massive volume of wastes that are being dumped in the environment). Is there anything that we can do about this? One suggested approach is to attempt to base economic and industrial materials flows upon those of ecosystems – in a manner similar to that of industrial
ecology. This approach certainly has potential, but is not in itself a panacea. The role of forests and farms in providing materials, fuels and industrial feedstocks in the future is also discussed. The rush to develop biofuels has often led to problems as economic factors rather than sustainable use have sometimes been the driver, and issues such as this are examined in order to provide lessons for the way that we should make a transition to a bio-based economy.

Hill demonstrates that a key issue is that economic activity is strongly coupled to both materials and energy use. No amount of incremental efficiency gains can ever allow us to compensate for the exponential nature of economic growth. Other authors have discussed the treadmill of economic growth in much detail, and thus Hill does not deal with this complex issue in depth. However, he does argue that changing the global economic system is not a realistic goal in the short or even medium term to resolve sustainability issues. Although it is possible for governments to mobilize huge financial resources to meet crises, systemic issues such the slow devastation of natural resources tend to pass beneath the radar. The application of technology to develop new energy systems and new ways of using materials is needed to address the root causes of environmental degradation. These technologies are entirely within our grasp today, but Hill suggests that their adoption will require global philosophical change, regardless of the financial driver for these efforts. Hill makes the point that the future approach must be one of strategic investment in new ‘green’ technologies, research development and, above all, the education of the next generation of people to facilitate this transition to a new industrial age. A key question Hill raises is whether governments of the world have the vision to provide the necessary resources to meet impending future environmental crises.

This text is an excellent introduction to the complex subject of sustainable resource use. It asks many questions and opens the eyes of the reader to the complicated issues surrounding the subject. It is a critical and insightful analysis of the subject matter, often drawing on historical examples, and encourages the reader to ask questions rather than taking matters at face value. At present, there are far too many claims being made for sustainable processes, or eco-friendly products, often based on very flimsy, if not false, data. This book gives the reader the opportunity to get under the skin of the assumptions that are often made to support such claims. Although written from the point of view of a physical scientist, the book is broad enough and clear enough to be understandable by a much wider readership. It is an excellent first text for this subject and contains a wealth of useful information. The text is also sprinkled with interesting anecdotes reflecting the author’s breadth of knowledge and his global perspective, permitting integration of details from diverse fields into larger themes to give the reader a complete understanding of problems and potential solutions to global natural resource use. This book will help to open a broader global discussion on the topic of true sustainability.

Barry Goodell
Head, Department of Wood Science and Forest Products
Virginia Polytechnic Institute and State University, USA

Jeffrey Howe
President, Dovetail Partners, Inc.
Minneapolis, USA
## List of Figures and Tables

### Figures

1.1 The principle behind Malthusian limitations ........................................ 6
1.2 The classic supply–demand curve ....................................................... 10
2.1 The principle of the Carnot heat engine ............................................... 21
2.2 The Carnot efficiency for a theoretical heat engine ............................. 22
2.3 An open system, a closed system and an isolated system .................. 23
2.4 Motion of an atom and of a diatomic molecule ................................... 27
2.5 Translational energy levels at different temperatures ......................... 28
2.6 The increase in entropy on moving from a solid through a liquid to a gas 28
2.7 The ‘Maxwell’s demon’ thought experiment ....................................... 31
2.8 The energy profile of a reaction ......................................................... 34
2.9 The principle of exergy and distance from thermodynamic equilibrium 35
2.10 The emission of electromagnetic radiation from the sun and Earth .... 39
2.11 Short wavelength photons from the sun reaching Earth .................... 39
2.12 Representation of photosynthesis ...................................................... 40
3.1 The main copper-producing countries of the world .......................... 45
3.2 The reserve to production ratio for copper ........................................ 46
3.3 The reserve to production ratio for global crude oil and natural gas .... 47
3.4 The famous Hubbert curve ............................................................... 48
3.5 The form of the logistic equation, a production history for a given resource, the cumulative production and be resultant Hubbert linearization of the data ......................................................... 49
3.6 A Hubbert linearization plot of production from the US48 .................. 49
3.7 Global copper production ............................................................... 50
3.8 Global production data for a range of metals .................................... 51
3.9 Examples of some log normal distributions ...................................... 52
3.10 A Hubbert linearization on an asymmetrical production curve ........ 52
3.11 Hubbert linearizations for a range of metal production .................... 53
<table>
<thead>
<tr>
<th>Figure/Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.12</td>
<td>Changes in the prices paid for some metals since 1900</td>
<td>59</td>
</tr>
<tr>
<td>3.13</td>
<td>The main processes involved in the production of copper metal</td>
<td>61</td>
</tr>
<tr>
<td>3.14</td>
<td>The criticality matrix</td>
<td>64</td>
</tr>
<tr>
<td>4.1</td>
<td>Plots showing increase in world population over the past 2000 years,</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>the predicted population increase based upon UN models with constant and low fertility rates,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the distribution of this population increase between more developed and less developed regions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(medium fertility model), and economic activity since 1750 as measured by GDP in 1990</td>
<td></td>
</tr>
<tr>
<td></td>
<td>International Geary-Khamis Dollars</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>The demographic transition</td>
<td>75</td>
</tr>
<tr>
<td>4.3</td>
<td>The environmental Kuznets curve</td>
<td>76</td>
</tr>
<tr>
<td>4.4</td>
<td>The change in sulphur emissions over time, GDP over time and sulphur emissions against GDP per</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>person, for the UK and Australia</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>The amount of CO$_2$ produced over time for the UK and US</td>
<td>78</td>
</tr>
<tr>
<td>4.6</td>
<td>The amount of CO$_2$ produced per unit of GDP over time</td>
<td>79</td>
</tr>
<tr>
<td>4.7</td>
<td>An economy showing a growth of 3% over 100 years and 1000 years</td>
<td>81</td>
</tr>
<tr>
<td>4.8</td>
<td>The influence of economic growth upon resource consumption</td>
<td>83</td>
</tr>
<tr>
<td>4.9</td>
<td>The growth in materials consumption in the US (1900–2006)</td>
<td>87</td>
</tr>
<tr>
<td>5.1</td>
<td>The linear throughput model</td>
<td>92</td>
</tr>
<tr>
<td>5.2</td>
<td>An example of materials flow analysis (MFA)</td>
<td>93</td>
</tr>
<tr>
<td>5.3</td>
<td>Lead production in Roman times recorded in the Greenland ice</td>
<td>95</td>
</tr>
<tr>
<td>5.4</td>
<td>Examples of three organic compounds produced by industry</td>
<td>96</td>
</tr>
<tr>
<td>5.5</td>
<td>The materials flows for lead in the US in 1970 and 1994</td>
<td>98</td>
</tr>
<tr>
<td>5.6</td>
<td>Copper flows associated with the US economy</td>
<td>99</td>
</tr>
<tr>
<td>5.7</td>
<td>Modification of the linear throughput system by a recycling loop</td>
<td>101</td>
</tr>
<tr>
<td>5.8</td>
<td>Different recycling levels and the dissipation of resources</td>
<td>102</td>
</tr>
<tr>
<td>5.9</td>
<td>The waste pyramid</td>
<td>105</td>
</tr>
<tr>
<td>5.10</td>
<td>The materials cascade</td>
<td>106</td>
</tr>
<tr>
<td>5.11</td>
<td>Embodied energies in MJ per kg for construction materials</td>
<td>107</td>
</tr>
<tr>
<td>6.1</td>
<td>The photosynthesis system boundary</td>
<td>119</td>
</tr>
<tr>
<td>6.2</td>
<td>The functioning of an ecosystem</td>
<td>120</td>
</tr>
<tr>
<td>6.3</td>
<td>The energy flows through a single trophic compartment</td>
<td>121</td>
</tr>
<tr>
<td>6.4</td>
<td>The biomass pyramid</td>
<td>122</td>
</tr>
<tr>
<td>6.5</td>
<td>The carbon biogeochemical cycle</td>
<td>125</td>
</tr>
<tr>
<td>6.6</td>
<td>The industrial symbiosis of the Kalundborg industrial park</td>
<td>127</td>
</tr>
<tr>
<td>7.1</td>
<td>Global bioethanol production by country</td>
<td>140</td>
</tr>
<tr>
<td>7.2</td>
<td>US bioethanol production</td>
<td>142</td>
</tr>
<tr>
<td>7.3</td>
<td>Fertilizer requirements of the main US agricultural crops</td>
<td>143</td>
</tr>
<tr>
<td>7.4</td>
<td>GHG emissions for biofuels compared with fossil fuel equivalents</td>
<td>144</td>
</tr>
<tr>
<td>8.1</td>
<td>Forested areas of the world</td>
<td>158</td>
</tr>
<tr>
<td>8.2</td>
<td>The top 13 countries for deforestation (2000–2005)</td>
<td>161</td>
</tr>
<tr>
<td>8.3</td>
<td>The global relationship between wealth and forestation</td>
<td>161</td>
</tr>
<tr>
<td>8.4</td>
<td>Ratio of fuelwood to wood products against wealth of country</td>
<td>162</td>
</tr>
<tr>
<td>8.5</td>
<td>Carbon capture and storage the natural way</td>
<td>163</td>
</tr>
<tr>
<td>8.6</td>
<td>Growth of forest biomass over 100 years</td>
<td>164</td>
</tr>
<tr>
<td>8.7</td>
<td>The forest as a net carbon source</td>
<td>166</td>
</tr>
</tbody>
</table>
8.8 Percentage of land covered in forest in Europe 167
8.9 The carbon balances associated with the use of timber products 169
9.1 Matter flows through society in a linear manner 185
9.2 Cyclic flows for materials that are not renewable 185
9.3 System boundaries and materials flows for different classes of materials 193
9.4 Stabilizing material consumption in a growing economy 196
9.5 The issue-attention cycle 198

Tables

3.1 Concentration of some metals present in the Earth’s crust 55
3.2 Concentration of some metals present in seawater 56
5.1 Carbon emissions associated with some common building materials 108
7.1 Types of cellulose nitrate 151
9.1 Annual energy subsidies for the energy industry (1995–1998) 201
9.2 UK GHG budgets for the next ten years 202
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>acidification potential</td>
</tr>
<tr>
<td>BASF</td>
<td>Badische Anilin- und Soda-Fabrik</td>
</tr>
<tr>
<td>BTL</td>
<td>biomass to liquids</td>
</tr>
<tr>
<td>CCA</td>
<td>copper/chrome/arsenic</td>
</tr>
<tr>
<td>CCF</td>
<td>continuous cover forestry</td>
</tr>
<tr>
<td>CCS</td>
<td>carbon capture and storage</td>
</tr>
<tr>
<td>CDM</td>
<td>clean development mechanism</td>
</tr>
<tr>
<td>CFC</td>
<td>chlorofluorocarbon</td>
</tr>
<tr>
<td>CO$_2$e</td>
<td>carbon dioxide equivalents</td>
</tr>
<tr>
<td>CST</td>
<td>crude sulphate turpentine</td>
</tr>
<tr>
<td>CTO</td>
<td>crude tall oil</td>
</tr>
<tr>
<td>DDT</td>
<td>dichlorodiphenyltrichloroethane</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change (UK)</td>
</tr>
<tr>
<td>DERV</td>
<td>diesel</td>
</tr>
<tr>
<td>DNSC</td>
<td>Defense National Stockpile Center</td>
</tr>
<tr>
<td>DP</td>
<td>degree of polymerization</td>
</tr>
<tr>
<td>DS</td>
<td>degree of substitution</td>
</tr>
<tr>
<td>DSM</td>
<td>De Nederlandse Staatsmijnen</td>
</tr>
<tr>
<td>DTO</td>
<td>distilled tall oil</td>
</tr>
<tr>
<td>EKC</td>
<td>environmental Kuznets curve</td>
</tr>
<tr>
<td>ELV</td>
<td>End of Life Vehicle</td>
</tr>
<tr>
<td>ERoEI</td>
<td>energy returned on energy invested</td>
</tr>
<tr>
<td>EP</td>
<td>eutrophication potential</td>
</tr>
<tr>
<td>ETP</td>
<td>eco toxicity potential</td>
</tr>
<tr>
<td>EU ETS</td>
<td>European Union Emissions Trading Scheme</td>
</tr>
<tr>
<td>FAME</td>
<td>fatty acid methyl ester</td>
</tr>
<tr>
<td>GAI</td>
<td>gross annual increment</td>
</tr>
<tr>
<td>Gb</td>
<td>gigabarrels of oil</td>
</tr>
<tr>
<td>GDP</td>
<td>gross domestic product</td>
</tr>
</tbody>
</table>
GHG | greenhouse gas  
--- | ---  
GPP | gross primary production  
GRACE | Gravity Recovery and Climate Experiment  
GWP | global warming potential  
HANPP | human appropriation of net primary production  
HTP | human toxicity potential  
ICI | Imperial Chemical Industries  
IPCC | Intergovernmental Panel on Climate Change  
JI | joint implementation (projects)  
LCA | life cycle assessment  
LCI | life cycle inventory  
LCIA | life cycle impact assessment  
LISS | low impact silvicultural system  
MFA | materials flow analysis  
NAI | net annual increment  
NASA | National Aeronautics and Space Administration  
NFRC | natural-fibre reinforced composite  
NO$_x$ | nitrous oxides  
NPP | net primary production  
ODP | ozone depletion potential  
odt | oven-dry tonnes  
OECD | Organisation for Economic Co-operation and Development  
PHA | poly(hydroxyalkanoate)  
PLA | poly(lactic acid)  
POCP | photochemical oxidant creation potential  
ppm | parts per million  
RFF | Resources for the Future  
RGGI | Regional Greenhouse Gas Initiative  
RoHS | Restriction on the Use of Hazardous Substances  
r/p | reserve to production (ratio)  
SI | Système Internationale d’Unités  
SUV | sports utility vehicle  
TBTO | tributyl tin oxide  
TCDD | 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin  
TOFA | tall oil fatty acid  
UNEP | United Nations Environment Programme  
UN FAO | United Nations Food and Agriculture Organization  
US48 | the contiguous 48 states of the US  
USDA | United States Department of Agriculture  
USGS | United States Geological Survey  
UV | ultraviolet  
WCED | World Commission on the Environment and Development  
WEEE | Waste Electronic and Electrical Equipment Directive
1 Background

(crisis? what crisis?)

Introduction

This is a book about material resources, why we use them, why we throw them away and how long we might expect to be able to keep on doing this. The way that we use these resources seems to be based upon the premise that they are plentiful, or even inexhaustible, and the way that we seem happy to discard them when they cease to please us relies upon the assumption that, in so doing, we do no lasting harm to the ecological functioning of the planet that supports us. The explosive growth in the production and consumption of materials that has occurred as a result of the Industrial Revolution is inextricably linked to economic growth. It is undeniable that these developments have led to significant advances in the material well-being of many people on the planet, but can we continue with this wasteful behaviour forever, or for fifty, or perhaps only ten more years?

In terms of resources, widespread concerns about the availability of petroleum supplies surfaced in the 1970s, when the oil embargo revealed the dependence of Western nations upon foreign suppliers. As a result of these crises, much attention was devoted to the use of resources and their possible exhaustion. Around this time, a voluminous literature appeared discussing the implications of resource use, population growth, economic growth and sustainability. Then, gradually, the crisis receded. The price of crude oil fell dramatically and the problems seemed to fade away. Recent rises in the prices of fossil fuels and many other resources have brought the whole issue into focus again. Simultaneously we are seeing that our activities are starting to have global consequences, such as the discovery that our use of chlorofluorocarbons in refrigerants and aerosol propellants was destroying the ozone layer that protects us from the sun’s harmful ultraviolet radiation (there were many sceptics at first) and now with the effects of anthropogenic activities upon the climate. We are seeing destruction of wilderness and appropriation of biological production on a scale that is unprecedented in the history of humanity. Sustainability is back on the agenda.
and in a big way. These issues are no longer just the province of a handful of ‘fringe’ environmentalists. This is big business.

Everyone is talking about sustainability. Every company has a strategy for dealing with the issues. We are bombarded with information about carbon footprints, recycling, environmental friendliness, biofuels, eco-friendly cars and green consumerism. Scientists everywhere seem to have part of the solution to this problem at their fingertips, but they need a little more money to finalize the research work. There are experts who have no difficulty pronouncing what needs to be done to solve the problems. They may even seek to make a meagre living from such activities, and who could begrudge them that?

Along with the message that we have to do something, there is another option. We can carry on behaving in the same way, but we have to do it ‘sustainably’ (the ‘S’ word). The system isn’t broken, it just needs a little bit of tinkering around the edges. By all means use retail therapy, but please read the eco-labels. Every manufacturer’s and trader’s website has the same message – this is how we are saving the environment, don’t buy our rivals’ products as they are not ‘sustainable’. There are commentators who insist that there is no problem at all, that if we are running out of something the market will tell us because the price will go up. Higher prices mean more innovation, or the search for substitutes. We don’t even seem to agree on whether global warming is anthropogenic in origin. It’s confusing to say the least.

This book is an attempt to try and make sense of it all. It is concerned with finding out whether there is a resource crisis or not and it seeks to determine whether or not it is possible for humanity to live on this planet in a sustainable way. It does not so much seek to provide the simple answers that some of the other books on this subject provide, but it does try to ask the right questions.

**Sustainability**

The concept of sustainability originates in agricultural and forestry production. A sustainable yield in this context is defined as the maximum amount of a commodity that can be harvested from a piece of land without compromising the ability of that land to provide the same harvest in the future. In terms of agricultural or forestry production, this is an easy concept to understand, although it is not necessarily so easy to quantitatively define where this limit lies.

During the presidency of Teddy Roosevelt in the US, Gifford Pinchot (the founder of the US Forest Service) was a strong advocate of the idea of a sustainable yield of timber. This led to the foundation of the Conservation Movement, with supporters of this approach arguing for the management of forests as tree farms in order to maximize timber production. This approach was opposed by John Muir and others in the Preservationist Movement who were concerned about the disappearance of pristine wilderness. Conservation has come to mean something different from this original idea.

As concerns about the environment began to increase, the United Nations (UN) hosted a conference on the Human Environment in Stockholm in 1972. At the end of this conference, the Stockholm Declaration on the Human Environment
was released, leading to the establishment of the United Nations Environment Programme (UNEP). One of the issues that had been considered at Stockholm was the polarization of concerns regarding the environment between rich and poor countries. Richer nations put concern for the environment high on the agenda, while for the poorer countries the over-riding issue was poverty alleviation. In 1974, the World Council of Churches held a conference on the subject of the use of science and technology for human development, at which they proposed a definition of a sustainable human society and examined what sustainability meant (Dresner, 2008).

The key issues were:

- There should be an equitable distribution of physical resources between all the peoples of the planet.
- All people should have the opportunity to participate in social decisions.
- The global capacity to supply food should exceed demand.
- Emissions of pollutants should not exceed the carrying capacities of ecosystems.
- The use of non-renewable resources should never exceed the increase in availability due to technological innovation.
- Human activities should not be negatively influenced by variations in global climate.

These show the necessity for human development and human concerns as an essential component in any definitions of sustainability. Without addressing these human needs, environmental concerns were seen as a luxury. Fritz Schumacher addressed this tension between rich and poor nations in his bestseller *Small is Beautiful* (Schumacher, 1973). In this book, Schumacher pointed out that the development strategies that had been employed in developing countries did little to alleviate the problems of the poor in the countryside and were based upon complex imported technology. He coined the term ‘appropriate technology’ to describe small-scale development projects where the technologies employed could be understood and controlled by local people.

**Economic growth**

What about the role of economics in providing for sustainable human development? It has been argued that some economic growth is necessary in order to allow for the development of the poor without creating social turmoil (Pirages, 1977). Economic development should be able to occur in developing countries in order to improve the living conditions of people trapped in poverty, yet simultaneously the wealthy should be able to maintain their standard of living. It is highly unlikely those who already have high standards of living would be willing to sacrifice them. Is it possible to achieve this? There certainly is potential to improve the conditions of developing countries by encouraging better and fairer trading conditions. In 1980, the International Union for the Conservation of Nature and Natural Resources (IUCN) published *The World Conservation Strategy* (IUCN, 1980). This report emphasized the importance of population pressure, poverty, social inequity and trading agreements disadvantageous towards poorer countries, as being primary causes of environmental degradation.
In 1983 the UN set up the World Commission on the Environment and Development (WCED) chaired by the Norwegian Prime Minister Gro Harlem Brundtland. In April 1987 the WCED published the famous document *Our Common Future* (WCED, 1987) which is often referred to as the ‘Brundtland Report’. In this publication, the meaning of the term sustainable development was defined as being:

> development which meets the needs of the present without compromising the ability of future generations to meet their own needs.

This is a simple and much quoted (and misquoted) definition, which means different things to different people. The published document contained the detail behind this definition to explain what the implications were:

- Environmental limits – these are not absolute limits, but there are limitations on the use of environmental resources due to the present state of technology and social organization and the ability of the biosphere to be able to deal with the wastes generated.
- Poverty – the elimination of poverty is essential to allowing all people to meet their aspirations for a fulfilling life.
- Participation – all of the people of the planet should be able to participate in decision-making at all levels.
- Equity – the way in which the resources of the planet are distributed should ensure that the poorer nations of the planet are able to undergo economic growth in order to improve the living conditions of their people. Those who lead more affluent lifestyles should modify their behaviour in order to ensure that they are living within the planet’s ecological means.

All of the above statements indicate that the issue is not so much one of insistence that there should be a fair apportioning of resources between generations (inter-generational equity) but rather, that the problems are here and now and therefore we should be concerned with intra-generational equity. It can also be understood that sustainability is about the environment, economics and society; these are the ‘three pillars’ of sustainability. It is impossible to have any one without the other two. However, the problem arises as to how it is possible to reconcile the needs of economic development for the poorer countries and economic growth for the rich countries with concerns about environmental limitations. Indeed, many developing countries believe that concerns for environmental protection are a luxury for the rich. It has been argued that the continuing appropriation of disproportionate amounts of the world’s resources by the wealthy nations is a factor leading to geopolitical destabilization. A sense of injustice, arising from the way that planetary wealth is distributed among the people of the planet, has been cited as one factor (among many) contributing to global terrorism (Richardson, 2006). The Brundtland Report is largely supportive of economic growth and points out that in order to allow the poor and rich countries to achieve some sort of parity it would be necessary to expand the world economy by a factor of 5 to 10. Since this is deemed to be impossible given the resource and environmental limitations, the report insists that these growth
requirements will have to be met by efficiency improvements. This leads us on to the Factor 10 arguments to be discussed later.

**Sustainability and capital**

Capital is usually associated with money in most people’s minds, but there are other ways of viewing capital. For the purposes of understanding sustainability it is useful to define least four types of capital. These are:

- **Human-created capital** – this is what we make, e.g. buildings, machines and infrastructure.
- **Natural capital** – air, water, soils, forests, natural resources like oil and minerals, ecosystem functioning, etc.
- **Human capital** – investment in health, education, nutrition, etc.
- **Social capital** – the institutions and culture that make a society function.

The way that sustainability is defined looks at how these four types of capital are managed. Crucial to this process is the degree to which one allows substitution between these different types of capital. This gives rise to the concepts of weak, sensible, strong and absurdly strong sustainability (Serageldin et al, 1994).

With weak sustainability, the total amount of capital remains the same, but no importance is placed on the composition of that capital. The assumption is that all forms of capital can substitute for one another equally. Sensible sustainability requires that in addition to maintaining the total capital stock, that the composition of the capital is important. Consequently, it is necessary to define thresholds below which a capital stock could not fall. The problem, of course, is in defining where these critical limits lie. Strong sustainability requires that each of the capital assets should be kept intact. Loss of forest in one area should be compensated for by increasing forest area elsewhere. Profits from exploiting oil resources should be used to develop renewable energy technologies. This view assumes that natural and human-made capital cannot be substituted for one another. Finally, absurdly strong sustainability assumes that non-renewable resources could not be used at all, or at a rate no greater than their geological replenishment rates. Renewable resources can only be used at a rate that does not compromise future productivity.

**Population growth and resources**

Concerns regarding the optimum population of humans that can be supported by the land stretch back to antiquity. Aristotle was of the opinion that the ideal nation state should keep the size of its population in accord with that of its land. One of the most famous works concerning the consequences of populations outstripping their resources is *An Essay on the Principle of Population* (1798) by the Reverend Thomas Robert Malthus (1766–1834). The essence of Malthus’s argument was that human
populations have a natural tendency to grow and that if such growth continues unchecked, then populations will always outstrip the ability of the environment to support them. To Malthus this inevitably meant that the ‘lower orders’ of society would be forever condemned to exist at a subsistence level. Furthermore, if any attempt was made to improve the conditions of the poor, the inevitable response would be an increase in population, with the result that the same miserable state of affairs would be rapidly reinstated. While populations have the property of increasing exponentially (geometrically), it is only possible to increase the area of land to support that population in a linear manner (arithmetically). The inevitable result is that the population rapidly reaches the limit that can be supported by the land. This is what is known in ecology as the ‘carrying capacity’ of the ecosystem. This idea is illustrated in Figure 1.1.

It is an inescapable mathematical property of exponential growth that it will always outstrip linear growth no matter what the linear multiplier is. This is called ‘explosive growth’ for a good reason. One of the principles underlying Malthus’s arguments is that the productive capacity of the land remains unchanged and that any increase in yield can only result from an increase in area. An alternative viewpoint was adopted by David Ricardo who noted that as population increased, progressively lower quality and marginal land would be cultivated. But the total available area of land is limited, nonetheless.

At this time the agrarian sector was the focus of almost all economic activity and, because of this, economic theories were based around issues linked to agricultural production. In the 1750s a school of economic thought developed in France based on the principle that natural resources and especially fertile agricultural land were the

---

**Figure 1.1** The principle behind Malthusian limitations

Note: The population increases exponentially while the area of land that can be converted to support that population increases linearly. The result is that the population is limited by the ability of the land to support it and, as a consequence, the population is condemned to exist at a subsistence level no matter what improvements are made.
basis of material wealth. This movement was known as Physiocracy and is considered to be the first organized scientific economic philosophy (Cleveland, 1987). The Physiocrats argued that the economic process was ultimately subject to the laws of nature and not human free will and that if the operation of the natural laws could be understood then it would be possible to maximize social welfare.

The limitation that land area placed upon the size of populations and economies was changed forever by the advent of what Frederick Engels called the ‘Industrial Revolution’. At the beginning of the Industrial Revolution, nearly every industrial raw material was supplied by agriculture or forestry. The single most important factor leading to the exponential growth of economies was the exploitation of fossil fuels, substituting for labour, water and wind energy. This sudden release from the constraints of the land and nature led to a population explosion in Europe that resulted in the emigration of around 60 million people to other parts of the world in the 19th century.

The Industrial Revolution

The Industrial Revolution represented a transition from the use of human and animal labour as the means of manufacturing goods and services to a machine-based economy. The beginnings of the Industrial Revolution can be traced back to innovations occurring in the agricultural and especially the textile processing sectors in the UK in the latter part of the 18th century. The improvements in agricultural efficiency combined with a reduced level of child mortality in the 17th century created a surplus rural population that sought employment in the textile industries. Initially a cottage industry, the increased utilization of water power led to the creation of large production units. The invention of the factory is often thought of as a creation of the Industrial Revolution, but the first factory in the modern sense of the term was actually built by the Republic of Venice in 1104. The Venice Arsenal built ships on assembly lines from manufactured parts, employed 16,000 people and reputedly launched a ship a day.

The evolution of the textile industry in the UK from a cottage industry using human-powered spinning and weaving to factories utilizing water-powered machines came about as a result of a few key inventions: the flying shuttle (1733), the roller spinning machine (1738), the carding machine (1748) and the spinning jenny (1764). The invention of the water-powered spinning frame by Richard Arkwright in 1768 enabled the move from home-based to factory-based textile production. This was followed by the construction of the world’s first water-powered textile mill at Cromford in England in 1771. The textile industry relied at first on the vastly increased production of wool from sheep grazing on land created by clearance and enclosure (incidentally displacing large numbers of people from rural areas and making a ready workforce for the textile industry). However, it was the introduction of cotton fibre that resulted in a huge expansion in the number of textile mills, especially in the northwest of England.

Another technological development intimately associated with the Industrial Revolution was the production of iron. Known as the metal of heaven to the Ancient
Egyptians, who used cold-worked meteoritic iron in implements and ornaments, the first smelted metal appeared around 3000 BC. Until about the 14th century, all of the iron produced was wrought iron, which needed a lot of hammering while hot to produce a usable material and which contained inclusions of slag and other impurities. Cast iron, an alloy of iron and carbon, required much higher processing temperatures and, although the technology had been developed in China as early as the sixth century, it was not produced in Europe until much later.

In the land where the Industrial Revolution was born, iron production was already established when the Romans invaded in AD 43. The industry was mentioned in the Domesday Book, but it was during the medieval period that production began to take off. Water power was used for the forging of iron and also to provide power for the air bellows of the first blast furnace in England, which was constructed in 1491 (at Buxted, in the Sussex Weald), allowing for the higher temperatures needed for the making of cast iron. Wealden iron became famous for the production of high quality cannons; many place names in Sussex attest to the dominance of this industry. Wealden cast iron was produced using charcoal derived from the extensive forests of the region and iron production in other parts of the country was similarly tied to the forests. However, Abraham Darby successfully produced cast iron using coke at Coalbrookdale in Shropshire in 1709. Cast iron from this furnace was used to make the world’s first iron bridge in 1779. Various improvements were made to the production processes over the years, but it was the introduction of the Bessemer process in the mid-19th century that allowed for the economic production of steel. For the first time in history it was possible to mass-produce a metal that was strong in tension.

Why is this so important? It was now possible to manufacture improved steam engine boilers operating at higher pressures relatively cheaply. Rails and bridges could be made that were much less prone to failure (the original Tay Bridge was made of cast and wrought iron – the new one incorporated steel). Powerful warships were built that travelled long distances with improved weaponry. The fact that the Industrial Revolution took hold initially in Europe, the US and Japan gave these countries a huge advantage in deciding how the resources of the planet should be allocated (Diamond, 1997). Political organization and the development of military power which was deployed globally using sophisticated maritime technologies allowed the European nations to have a dominant role in shaping world events. The evolution of industrialized societies, supported by coal, the use of steel and the motive power of the steam engine along with the rise of the chemical industry resulted in the ability of countries in possession of such knowledge to dominate those who did not possess it. Another more insidious factor was the general lack of immunity of indigenous populations to the various pathogens carried by explorers and their entourages. Science and technology were indeed proving to be able to alleviate the conditions of some of the people on the planet, but, unfortunately, at the expense of others.

We now find ourselves in a position where we are affecting the functioning of the planet. We are fast approaching real limits to what we can do. The predictions made in the past were not really wrong, but they were premature.
Limits to growth – a brief history of the ideas of resource-constrained economics

The predicted Malthusian collapse did not occur. The Industrial Revolution brought with it new technologies and new ways of creating wealth which did not rely on the land. Improved farming methods and the use of fertilizers and, later, pesticides increased crop yields enormously. Populations in the richest countries of the world began to stabilize. These were all things that Malthus could not have foreseen. However, the principle that exponentially increasing populations or exponentially increasing economies could exhaust their resource base has continued to occupy the thoughts of many. Environmental Quality in a Growing Economy (Jarrett, 1966) contains an essay ‘The Economics of the Coming Spaceship Earth’ by Kenneth Boulding, which argues that during the historical era human impact on the environment has been insignificant due to a low population. Any problems that did occur were localized and could be dealt with by moving to other regions. There was always a frontier, beyond which lay the wilderness where wastes could be disposed of with impunity. Boulding referred to this as a ‘cowboy economy’ because this conjured up the image of the endless frontier associated with American cowboys. However, in the contemporary era there was no frontier left and it was no longer possible to dispose of wastes without deleterious consequences. The photograph of Earth brought back by Apollo astronauts in 1969 brought this idea to life.

Towards the end of the 1960s Paul Ehrlich argued in his influential book The Population Bomb (1968) that the exponentially increasing world population would result in catastrophic famines in the 1970s and 1980s. It was also controversially concluded that giving aid to countries that did not take steps to deal with population growth was pointless and would merely encourage further population increases. This is very reminiscent of the position that Malthus adopted and it attracted widespread criticism. Another book pointing out the resource implications associated with exponential growth was Limits to Growth (Meadows et al, 1972, 2004). The authors reported on the results from a computer model of the impact of population and economic growth upon the Earth’s ecosystems. Under various scenarios, the model showed that the human population would overshoot the carrying capacity of the planet before the end of the 21st century. However, the Malthusian perspective that these and other books represent has been criticized on a number of grounds over the years. A good overview of this debate is given by Hussen (2004).

Growth without limits – the role of technology and the arguments of classical economics

Socialist philosophers in Revolutionary France agreed with Malthus that there was a danger of overpopulation, but they considered that the solutions to this ever-present threat lay in proper social and economic organization and also in the application of technology to give everyone an improved standard of living. Engels similarly believed that the impact of a rising population would be compensated for by constant
improvements arising from the application of science and technology. This idea has always been a theme within classical economics and although once associated more with the left of the political spectrum, it has become increasingly identified with the politics of the right. The economist Julian Simon has written extensively on the ability of human ingenuity to overcome any physical limitations on economic growth and argued that an increasing human population is a good thing, because it means more brains and hence more ideas (Simon, 1996). We shall examine this argument in more detail in Chapter 3. Both John Locke and Adam Smith argued that economic self-interest could be the motive force for ensuring the common good and such opinions continue today in the free-market economic philosophy. Put simply, the free-market view of resources takes the following positions. The scarcity (or otherwise) of a resource is reflected in its price on the free market. If demand increases and supply does not, then the price increases. Price increases lead to reduced demand and the price will consequently fall; leading to a self-correcting mechanism. This is the familiar supply–demand curve (Figure 1.2).

However if the demand for a resource does not fall and the price stays high, this provides the incentive for:

- the exploitation of more marginal resources which have a higher cost of extraction;
- increased activity in exploration to go and look for new resources;
- increased efficiency in the use of that resource through (for example) higher levels of recycling;
- research into the use of alternative resources.

The last two activities would be the correct market response if it was not possible to increase production due to the absolute scarcity of the resource. The argument then follows that it is unnecessary to take any action because the market itself provides the best possible mechanism for dealing with scarcity. This is the self-correcting ‘invisible

---

**Figure 1.2 The classic supply–demand curve**

Note: This demonstrates the self-correcting mechanism of the free market.
Background

hand’ of the market in operation as introduced by Adam Smith (Smith, 1776). Hotelling (1931) was able to use classical economic methods to show that there was an optimum rate at which resources should be depleted. Traditional economics asserts that natural capital and manufactured capital are interchangeable (fungible) and that the loss of one can be compensated for by an increase in the other. It assumes that resources are substitutable and that any local constraints upon economic growth can be alleviated through inter-regional trade. As far as equity is concerned, the best way to alleviate poverty is to allow unfettered economic growth so that everyone will get rich (‘trickle-down’ effect) which takes care of intra-generational equity. As for the future people of this planet, the classical economic view is that they are the rich ones and we the poor because of the abundant wealth produced through continual economic growth into the future. Based upon these ideas, there is no need to be concerned about running out of resources because the market is able to respond through price changes which encourage corrective actions. In a classic study of the economic costs of resources, Barnett and Morse (1963) were able to show that the prices of resources had actually declined in real terms between 1870 and 1957; other studies performed since then have come to similar conclusions. From the viewpoint of classical economics, this appears to account for the resource limitation argument, but what about wastes?

Externalities

Assuming that the relative abundance of resources is dealt with efficiently by market forces, can the same be said about impacts on the environment? How does the market deal with these? A number (by no means exhaustive) of scenarios can be envisaged where the economic position would seem to be at odds with that of common sense:

- A range of mountains in a water catchment is deforested in order to derive economic value from the timber. As a consequence flooding, landslides and soil erosion occur, which inundate low-lying farmland causing huge economic damage.
- Heavy metal pollution from a mine seeps into an underground water body. This subsequently makes its way into the drinking water of a nearby town, but some years after the mine has closed. The public sector has to pay for expensive water treatment facilities. The mining company which derived economic benefit from extracting the metal ore has moved on, or perhaps went out of business once the mine was exhausted.
- Coal-burning power stations produce sulphur dioxide which is an atmospheric pollutant causing respiratory disorders in the local population. The cheapest way to get around this problem is to build very high chimneys so that the pollutant is no longer deposited locally. However, the effect is felt hundreds of miles away in a neighbouring country where it causes damage to forests and fisheries at great economic cost.
These are all examples of negative externalities, where the costs associated with the problem are not borne by the originator. Negative externalities are examples of damage occurring to what is sometimes referred to as the ‘global commons’, in other words the environment.

**The tragedy of the commons**

‘The tragedy of the commons’ was the title of an article written by Garrett Hardin, published in the journal *Science* (Hardin, 1968). In it Hardin discussed the conflict arising between the desires of individuals to maximize their appropriation of goods or services from a common resource, which is in conflict with the requirement that correct management of this resource requires that each person should limit their exploitation.

The example put forward by Hardin is that of a village with a common pasture, where each villager tries to keep as many animals as possible. The rationale behind the argument is that each individual may seek to increase their own well-being by adding one more animal to their herd, with the expected results. This encourages the addition of more and more animals until the unintended consequence of land degradation, with an attendant collapse in both the animal and human populations, occurs. In the analysis of the behaviour of the villagers in degrading the commons, Hardin takes issue with the idea of the behaviour of individuals resulting in the common good through the mechanism of the ‘invisible hand’ as advocated by the Scottish essayist Adam Smith in *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776).

Hardin also considers the consequences of an increasing global human population and the burden that this puts upon the Earth’s resources, coming to the conclusion that in order to maximize population, it is necessary to minimize individual consumption, with every person ultimately having to rely upon a subsistence diet. This prognosis is clearly Malthusian in its philosophical foundations and in direct contrast with the no-limits Panglossian hypothesis advanced by Julian Simon, where an increase in population means more minds, more innovation and an increase in everything for all. Which of these two schools of thought is the more accurate – if either? One issue which over-rides the ideas put forward by Simon relates to the energy required to process materials and to provide goods and services, and this is the ultimate argument put forward by Hardin.

Even if an infinite source of energy could be found, the problem would then become one of dissipation. The inescapable downgrading of any energy source to heat means that there is a limit to how much energy can ultimately be used. The emission of waste heat in an exponentially increasing economy would eventually result in the Earth glowing red-hot. There are limits to growth. Even if physical limitations could be overcome indefinitely through the application of technology (an impossibility), we then run up against immovable and irrevocable thermodynamic limits.