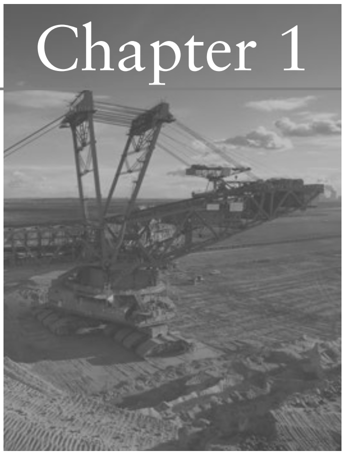
Chapter 1



Understanding the Earth's Natural Resources: An Introduction

> *"The conservation of our natural resources and their proper use constitute the fundamental problem which underlies almost every other problem of our national life"*
>
> *– Theodore Roosevelt*

Resource issues are central to the important challenges facing the world today. They are woven into society at every level as materialistic lifestyles compete with each other and with subsistence living for limited resources. A resource is something that can be used, an asset. On earth these can be divided into living and nonliving resources. This text considers the nonliving ones as given in the grey boxes in **Figure 1.1**. The arrows indicate that energy must be added to rocks, the atmosphere, and water to produce the natural resources shown. Humankind adds most of this energy before a resource is useful but, as shown by the open arrows, some resource production is dominated by the natural input of energy.

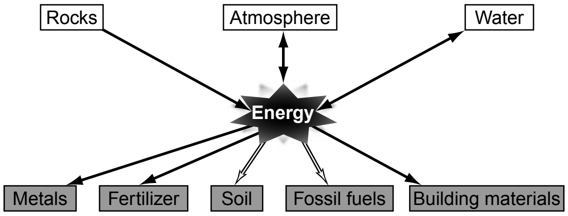


Figure 1.1 Resource relationships on the earth.

Energy resources are anything used by society as a source for the ability to do work and include coal, crude oil, and natural gas as well as wind and the flow of water, among others. The first three energy resources are termed *fossil fuels* because they have been formed from the organic remains of prehistoric plants and animals.

Two ways to compare resources are shown in **Figure 1.2**. On the top in (**a**) are the top 10 mineral resources by quantity taken from the earth and on the bottom in (**b**) are resources ordered by their values. As might be expected, sand plus gravel and aggregate dominate the volume produced, but crude oil is by far the natural resource of greatest value.

Resources can be renewable or nonrenewable. *Renewable resources* are sources of energy or other natural material that are replenished shortly after being used. Renewable resources can depend on the rate of consumption. For instance, the amount of fish consumed on the earth is close to its maximum sustainable yield. If the consumption exceeds this value fish become a nonrenewable resource. Renewable resources include the following:

solar energy,
organic matter and its derivatives (food),
water,
wind,
forests, and
fish.

Nonrenewable resources are natural resources that cannot be remade, regrown, or regenerated

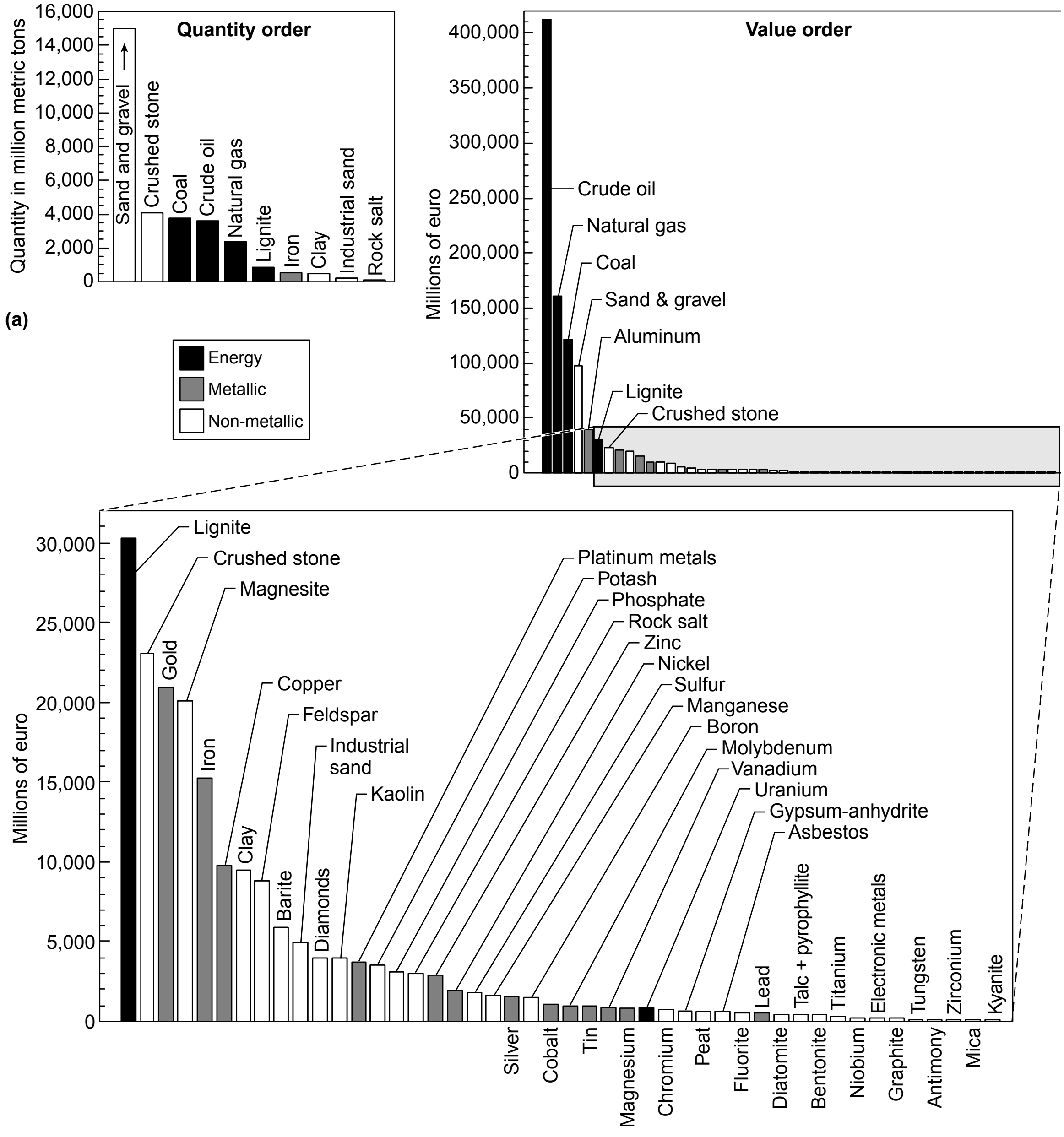


Figure 1.2 Resource production in 1998 (**a**) by quantity (iron given in metal equivalent and natural gas in 1,000 million m^{-3}) and (**b**) by value. Inset in (**b**) is an expansion of the low value resources. (Data from: Wellmer, F. W. and Becker-Platen, J. D., 2002, Sustainable development and the exploitation of mineral and energy resources: a review, *Inter. Jour. Earth Sci.,* v. 91, pp. 723–745.)

on a time scale comparative to its consumption. These resources are consumed faster by humankind than they are produced by nature and therefore the amounts decrease with time. Nonrenewable resources include fossil fuels and metals extracted from the earth as shown for copper in **Figure 1.3**. Geothermal energy, which is heat extracted from the earth, is also nonrenewable as the extraction

Figure 1.3 Bingham Canyon copper mine in Utah is the largest excavation (Over 4 km wide) and the deepest open pit mine (Over 1.2 km deep) in the world.

cools the earth locally over human time scales. However, if the total heat output from the earth is considered then the potential to develop geothermal energy is almost limitless.

Energy and Resources

The earth is in a dynamic state powered by *energy*. This energy comes from a *flux* of sunlight through the earth's atmosphere and a heat flux through rocks from the earth's hot interior. By flux what is meant is the flow of mass or energy through a unit surface area per unit time. The energy flux average over a year at the top of the atmosphere from the sun is 1,360 joules per meter squared per second ($J\ m^{-2}\ s^{-1}$). Because 1 watt = 1 joule per second, the average flux of energy from the sun is 1,360 $W\ m^{-2}$. This is much larger than the average heat flux from the interior of the earth through the top of the crust, which typically varies from 25 to 150 $mW\ m^{-2}$ (mW = milliwatt = 10^{-3} watt) and averages 75 mW. Therefore, the interior heat flux is too small to affect the temperature or the earth's weather.

The average amount of energy from the interior of the earth that fluxes through an area of 36.5 m × 36.5 m is on average only about

$$36.5\ \text{m} \times 36.5\ \text{m} \times 0.075\ \text{watts m}^{-2} = 100\ \text{watts}. \quad [1.1]$$

If all this heat was captured and completely converted to electricity it could power a 100-watt light bulb. Not a lot of energy. However, the energy from this internal heat flux is not evenly distributed across the earth. As a result there are tectonically active areas where the heat flux is much higher. Heat in these high-energy areas, as well as energy from the sun, cause reactions that can concentrate minerals of interest and other natural resources. This text explains how.

Mineral Resources

Modern industrial societies are dependent on energy, water, and mineral resources to produce the goods and services needed. Informed citizens understand their dependence on energy and water as they are used directly and fluctuations in their price are felt immediately. Mineral resources on the other hand are incorporated into finished goods and the connections are not as obvious but the dependence is just as great. Every American born in 2008 is estimated to use the amount of nonfuel mineral resources given in **Table 1.1** in their lifetime. Again, these are generally not used directly but appear in finished products, some of which are outlined in the table.

The estimated average amount of energy by source used every year by an American is outlined in **Table 1.2**. **Figure 1.4** shows what the energy source was used for. The petroleum obtained from crude oil is consumed dominantly in passenger transportation. An average U.S. passenger car or light truck is driven about 12,000 miles (~19,300 km) a year and averages about 20 mpg (~32 km per gallon) so the vehicle consumes 600 gallons of petroleum per year.

The rest of the petroleum consumed in the U.S. is used as jet fuel, to produce heating oil, to make plastics, and as the asphalt base for roads. The coal and uranium are consumed dominantly to make electricity. However, some coal is used to produce heat for industrial applications. Much of the electricity is used by industries that make finished products. About 1/3 of natural gas goes into the production of electricity, 1/3 for heating

Table 1.1 Estimated nonenergy mineral resources used by an American over a lifetime.

MINERAL COMMODITY	AMOUNT REQUIRED OVER A LIFETIME	USES
Aluminum (bauxite)	5,677 pounds	Building supports, beverage containers, autos, airplanes
Cement	65,480 pounds	Roads, sidewalks, buildings
Clays	19,245 pounds	Floor and wall tile, bricks and cement, paper, dinnerware
Copper	1,309 pounds	Plumbing, electrical wire
Gold	1,576 ounces	Jewelry, electronic products
Iron ore	29,608 pounds	Mainly steel
Lead	928 pounds	Batteries, TV screens
Phosphate rock	19,815 pounds	Fertilizer, animal feed supplements
Stone, sand, and gravel	1.61 million pounds	Roads, concrete, asphalt, building blocks
Zinc	671 pounds	Metal rust inhibiter, paint, skin creams

Data from: U.S. Geological Survey and U.S. Energy Information Administration; statistical analysis from the National Mining Association.

Table 1.2 Estimated average amount of energy used by each American by source for 2010.

SOURCE	PETROLEUM	COAL	NATURAL GAS	URANIUM (0.72% = U^{235})
Volume or weight	1,055 gallons	7,540 lbs	72,980 cu. ft	1/3 lb
Energy content	1.2×10^{11} J	7.0×10^{10} J	8.3×10^{10} J	3.0×10^{10} J

J = joules.

Data from: Mineral Information Institute, Golden, Colorado.

buildings, and 1/3 for industrial uses. Natural gas vehicle fuel at present accounts for only 0.15% of the natural gas used.

Determination of Resource Prices

In general, a resource sold as liquid or gas is measured by a standard volume. In the case of liquids this is typically a barrel = 159 liters = 42 U.S. gallons. For gases such as natural gas a volume given by cubic feet or meters at a standard pressure and temperature is used. Solids, like minerals, use a standard weight. This varies from carats for gemstones to *metric tons* for industrial minerals. A metric ton is 1,000 kg while a carat is 0.0002 kg.

For a given mineral commodity prices occur at various stages of production. Consider bauxite, the rock material from which aluminum metal is obtained. Bauxite contains the minerals gibbsite, $Al(OH)_3$, boehmite, AlO(OH), and diaspore,

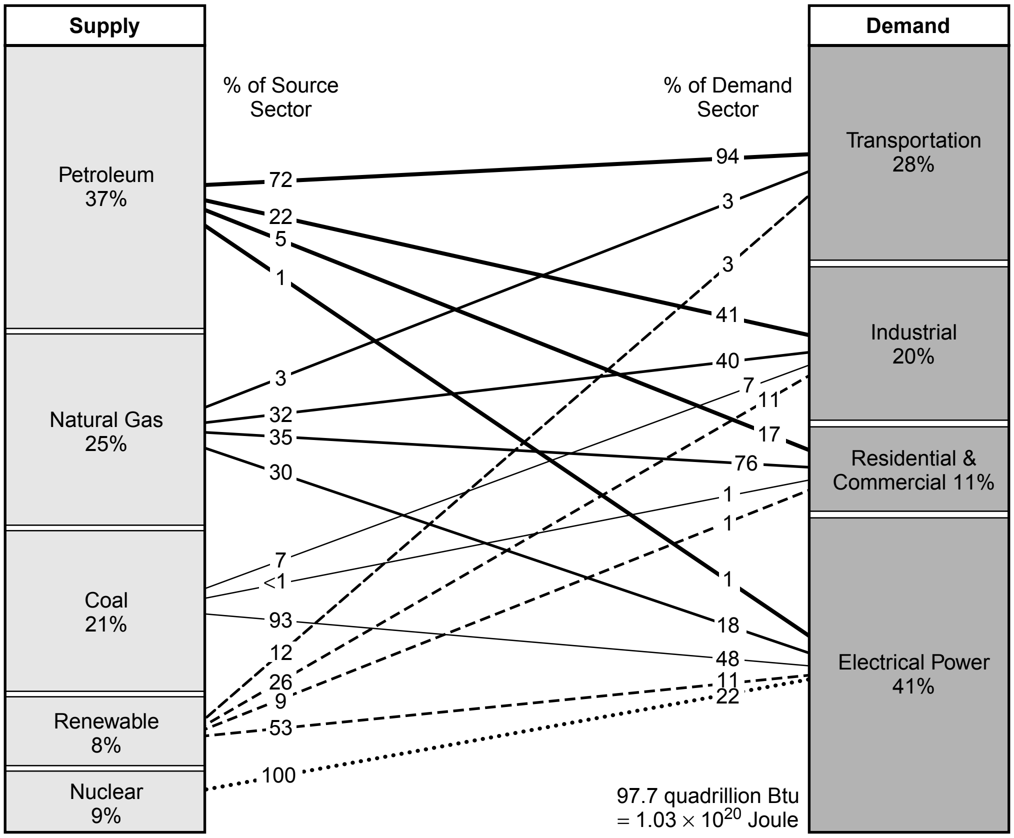


Figure 1.4 Energy supplied by type and what it was used for in the U.S. for 2010. Note renewable includes hydroelectric power. (Modified from USA Energy Information Administration, Department of Energy.)

AlO(OH). The price of bauxite with a content of about 50 wt% alumina, Al_2O_3, was about U.S. $65 per metric ton in 2012. Bauxite is processed and converted to nearly pure alumina that costs about U.S. $365 per metric ton. To produce 1 metric ton of alumina requires about 2 metric tons of 50 wt% alumina bauxite and about 1.3×10^{10} J of energy. The alumina is then processed to make Al metal. A ton of Al metal requires about 2.5 tons of alumina and 16 thousand kWh (kilowatt hours) of electricity or 5.8×10^{10} joules of energy. A metric ton of Al metal costs about U.S. $2,200. Prices can change for any of the three Al commodities depending on demand and the cost of energy.

Prices are determined by different techniques. Each is an effort to stabilize prices with changes in demand. The producer can announce the price as well as the terms and conditions for meeting a demand. These are producer prices. Resource prices are often set by a trade association or periodical that determines prices by recent transactions that have taken place. Markets exist for metals such as the London Metal Exchange (LME), and the United States Commodities Exchange (COMEX) for metal's futures and option trading. Alternatively, the buyer and seller can negotiate a price directly. These are then contract prices that typically extend over a number of years with provisions for price adjustments depending on the changes in costs of energy needed, etc. Prices can also be established by auctions open to anyone on future markets such as the Shanghai Futures Exchange (SHFE).

Resource Classification

There are many ways to classify resources. In this text a classification of resources based on their desired properties is used. Therefore, broad divisions of energy, metals, building and industrial materials, water, and soil are considered and then these are subdivided to produce the following topics:

Energy Resources
- Petroleum *(Chapter 2)*
- Natural Gas, Coal, and Related Resources *(Chapter 3)*
- Alternative Energy Resources *(Chapter 4)*
- Nuclear Power *(Chapter 5)*

Metal Resources
- Abundant metals *(Chapter 6)*
- Scarce Metals
  - Ferroalloy Metals *(Chapter 7)*
  - Base Metals *(Chapter 8)*
  - Precious and Specialty Metals *(Chapter 9)*

Life Supporting Resources
- Building and Industrial Minerals *(Chapter 10)*
- Chemicals from Evaporation of Water and Gaseous Elements from Air *(Chapter 11)*

Water and Soil Resources
- The Distribution and Movement of Water *(Chapter 12)*
- Water Quality, Usage, and Law *(Chapter 13)*
- Soil as a Resource *(Chapter 14)*

Given in the Table of Elements, following the Preface, are the elements considered in this text and the chapter where they are discussed. This can be found in the beginning pages of the book. Appendix A gives metric multipliers used for the resource units and Appendix B outlines some common ore minerals. Energy and power unit conversions are tabulated in Appendix C. A glossary of the terms introduced as given in italics when first used can be found in the back of the text and a geological time scale that gives the names of various times periods in earth history is presented on the inside back cover.

Mineral Resources and Reserves

The importance of energy and mineral resources to humankind is clear by considering a historical perspective of civilizations. Historians define civilizations based on their use of energy and mineral resources as given in **Table 1.3**. Note that we are presently making the transformation to the nuclear plus renewable energy age and petroleum will no longer define our existence. How will we make this transition? This text will consider our use of petroleum, nuclear, and renewable energy going forward as well as the other resources modern society depends on.

Table 1.3 Historical age and its approximate time period.

AGE	APPROXIMATE PERIOD
Paleolithic (Old Stone)	500,000 to 9,500 BC
Neolithic (New Stone)	9,500 to 5,000 BC
Bronze	5,000 to 700 BC
Iron	700 BC to 200 AD
Coal	200 to 1,850 AD
Petroleum	1,850 AD to present
Nuclear/Renewable Energy	Future

Resource Evaluation

Understanding the extent of fossil fuel and mineral resources and reserves in a particular property is the basis of determining its value. This includes production cost estimates as well as the varieties of fossil fuel and mineral products contained in the property. Fossil fuel and mineral reserves are then determined by a combination of the economics of extraction and processing operations, and specifics of the market for the fossil fuel/mineral products. Extractions of fossil fuel/mineral reserves are limited by either their physical exhaustion or loss of economic viability.

For a resource to become a *reserve* the location, concentration, quality, and quantity of the resource must be known or estimated using geological insight. It must also be extractable economically under current market conditions. To reflect varying degrees of geological certainty, resources can be subdivided into measured, indicated, inferred, and undiscovered categories as given in **Figure 1.5**.

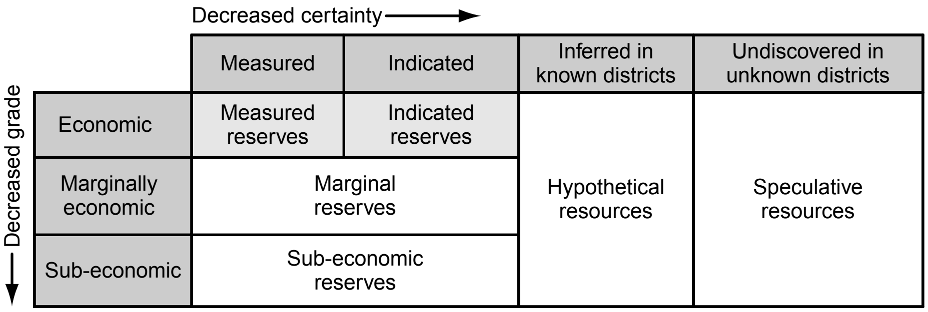
Measured reserves: The size of measured reserves is estimated from examination of outcrops, trenches, road cuts, and/or drill holes. The amount present is determined by physical and chemical analysis of samples. The sampling and geological observations are so closely done that the size, shape, depth, and changes in concentration of the resource are well established. Geophysical methods such as seismic sections and magnetic, electrical, and gravity surveys can be used to confirm the extent of the reserve.

Indicated reserves: The size and concentration of indicated reserves are estimated from information similar to that used for measured resources, but the sampling and observations are less frequently spaced. The degree of assurance, although lower than that for measured resources, is high enough to reasonably assume geological continuity between sampling and observations.

Inferred resources: For inferred resources estimates are based on geological evidence and assumed continuity in the geological processes operating in the area but there is less confidence than for measured or indicated reserves. Because of the uncertainty these are considered a resource rather than dependable reserves. Inferred resources need not be based on sampling or other measurements. However, the inference needs to be supported by a geological understanding of the resource formation process and particulars of the area considered.

Possible resources: Estimates of possible resources are based on broad geological knowledge and an economic model. There is less confidence than for inferred resources. The time lines for possible production are much longer so economic changes over time become more important.

Often the term *reserve base* is used in considering resource availability. In resource analysis this is typically the sum of measured reserves + indicated reserves + marginally economic reserves + a portion of subeconomic reserves (see Figure 1.5).



	Measured	Indicated	Inferred in known districts	Undiscovered in unknown districts
Economic	Measured reserves	Indicated reserves	Hypothetical resources	Speculative resources
Marginally economic	Marginal reserves			
Sub-economic	Sub-economic reserves			

Figure 1.5 Relation of reserves to resources for materials found in the earth.

Geochemical Cycles

An important broad way to view resources is in the context of *geochemical cycles*. A geochemical cycle indicates chemical changes in terms of fluxes between reservoirs on a particular time scale and generally considers the whole earth. These reservoirs can include the solid earth, ocean, and atmosphere.

Water Cycle

As an example of a geochemical cycle, consider the present day *water cycle*. This outlines the changes in the amount of H_2O in reservoirs on the present earth, as given in **Figure 1.6**. Note that a reservoir is in *steady state* and, therefore, does not change its size with time when the flux of H_2O, as given by the arrows, into a reservoir is equal to the flux out. Therefore, as shown in the figure the amount of water on the continents is in steady state.

The amount of H_2O in the atmosphere is also in steady state as the H_2O that precipitates as rain and snow on the continents, 110×10^{15} kg per year, together with that which precipitates on the ocean, 380×10^{15} kg per year, is equal to the sum of H_2O that transpires from plants and evaporates from wet surfaces on the continents, 70×10^{15} kg per year, together with that which evaporates from the ocean. Whether a reservoir is in steady state or not depends on the time frame considered. Clearly the size of the continental H_2O reservoir has changed over a 100,000-year time frame as the amount of ice in ice sheets has expanded and contracted during the earth's most recent ice ages. Also, if global warming occurs the amount of water in the atmosphere will increase if the average relative humidity in the atmosphere stays constant.

Carbon Cycle

A particularly important geochemical cycle for resource considerations is that for carbon. This is because humankind—through fossil fuel and biomass burning—is interfering with the natural balances of carbon in the cycle as shown by the long dashed arrows in **Figure 1.7**. The cycle is more complex than the hydrological cycle because carbon can exist in a variety of compounds, both organic and inorganic.

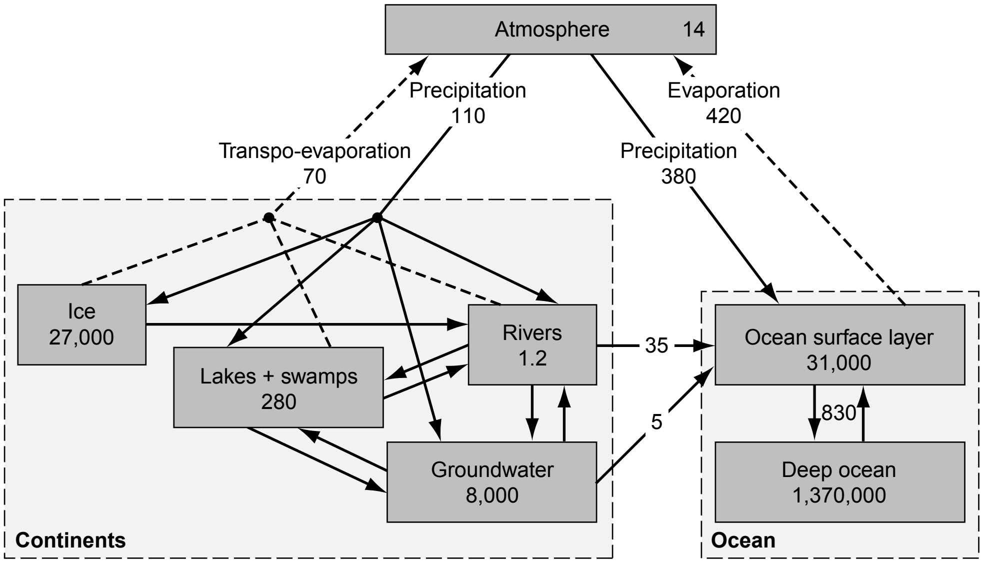


Figure 1.6 Present day water cycle with boxes denoting reservoirs of the indicated size in Eg (Eg = exagram = 10^{18} g) and arrows showing the fluxes in Eg yr^{-1} between the reservoirs.

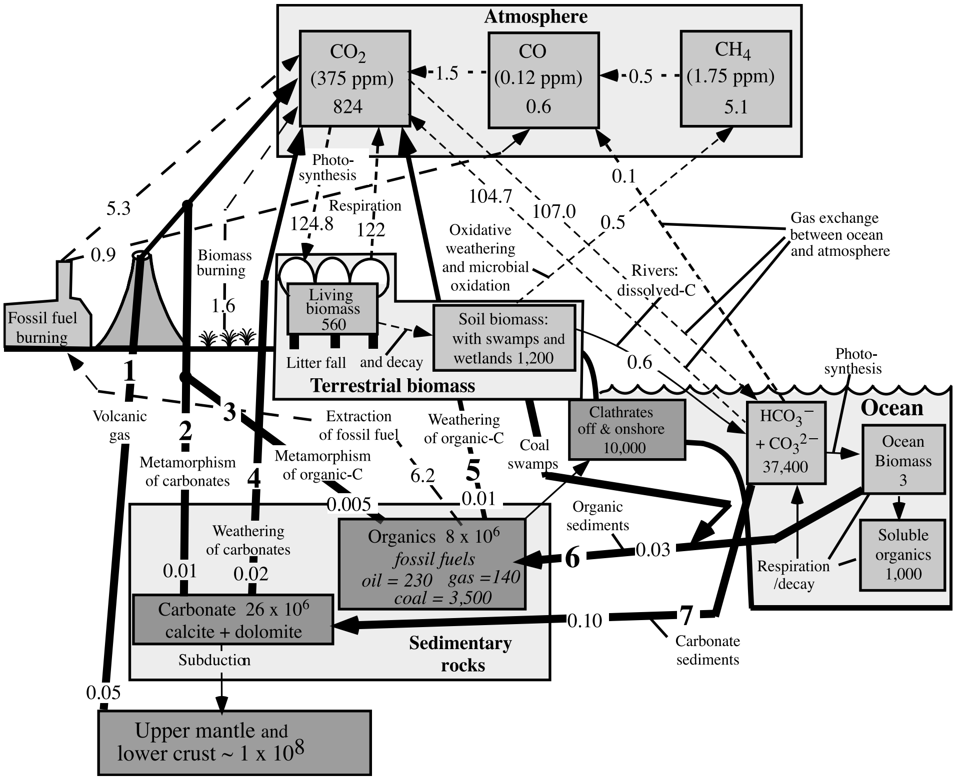


Figure 1.7 Carbon cycle in the year 2005 for the whole earth showing the reservoirs of carbon (units of Pg) as boxes and major fluxes (units of Pg yr^{-1}) between reservoirs given as arrows (Pg = 10^{15} g).

Table 1.4 tabulates the flux of grams of carbon into and out of the atmospheric CO_2 reservoir as given in Figure 1.7. Note that this reservoir is not in steady state as 3.4 Pg (Pg = petagram = 10^{15} g) per year more carbon fluxes into the atmosphere than fluxes out. Judging from the anthropogenic flux this increase is due to humankind's input of carbon into the atmosphere.

CO_2 in the Atmosphere

Shown in **Figure 1.8** are measurements of the CO_2 concentration of air as a function of time at the Mauna Loa Observatory in Hawaii, the "Keeling curve." The curve is named for the late Charles Keeling of the Scripps Institution of Oceanography, who had been undertaking the measurements until his death in 2005. Note the yearly cycle of CO_2 that declines in the spring when photosynthesis, and therefore the growth of plants, is at its maximum in the Northern Hemisphere. In the autumn CO_2 increases as photosynthesis decreases and dead vegetation starts to decay, releasing CO_2 and CH_4 to the atmosphere. Written in terms of equations, these observations are as follows:

$$\text{Spring: } H_2O + CO_2 + \textit{sunlight} \rightarrow CH_2O_{(\text{organic matter})} + O_2 \quad [1.2]$$

$$\text{Fall: } CH_2O_{(\text{organic matter})} + O_2 \rightarrow H_2O + CO_2. \quad [1.3]$$

Burning of carbon containing fossil fuels in the autumn and winter to generate heat also contribute significantly to the yearly cycling of CO_2. This can also be represented by reaction [1.3].

Figure 1.8 shows an increase in CO_2 on a year-to-year basis. Anthropogenic contributions to this increased concentration of CO_2 are due to the clearing of forests, which decreases the photosynthetic CO_2 sequestering effect, labeled

Table 1.4 PRESENT-DAY CARBON FLUXES INTO AND OUT OF THE ATMOSPHERIC CO_2 RESERVOIR*.

ATMOSPHERIC CO_2 RESERVOIR (UNITS OF Pg CARBON YR^{-1})	
FLUX IN	**FLUX OUT**
122.0 = Respiration	124.8 = Land photosynthesis
104.7 = Ocean degassing	107.0 = Ocean absorption
5.3 = Fossil fuel burning	**231.8 = Total**
1.5 = Oxidation of CO	
1.6 = Biomass burning	
0.1 = Long-term fluxes from mantle + crust (shown with thick lines)	**In – Out** = 235.2 – 231.8 = 3.4 Pg/yr
235.2 = Total	

*As given in Figure 1.7 in Pg (= 10^{15} g).

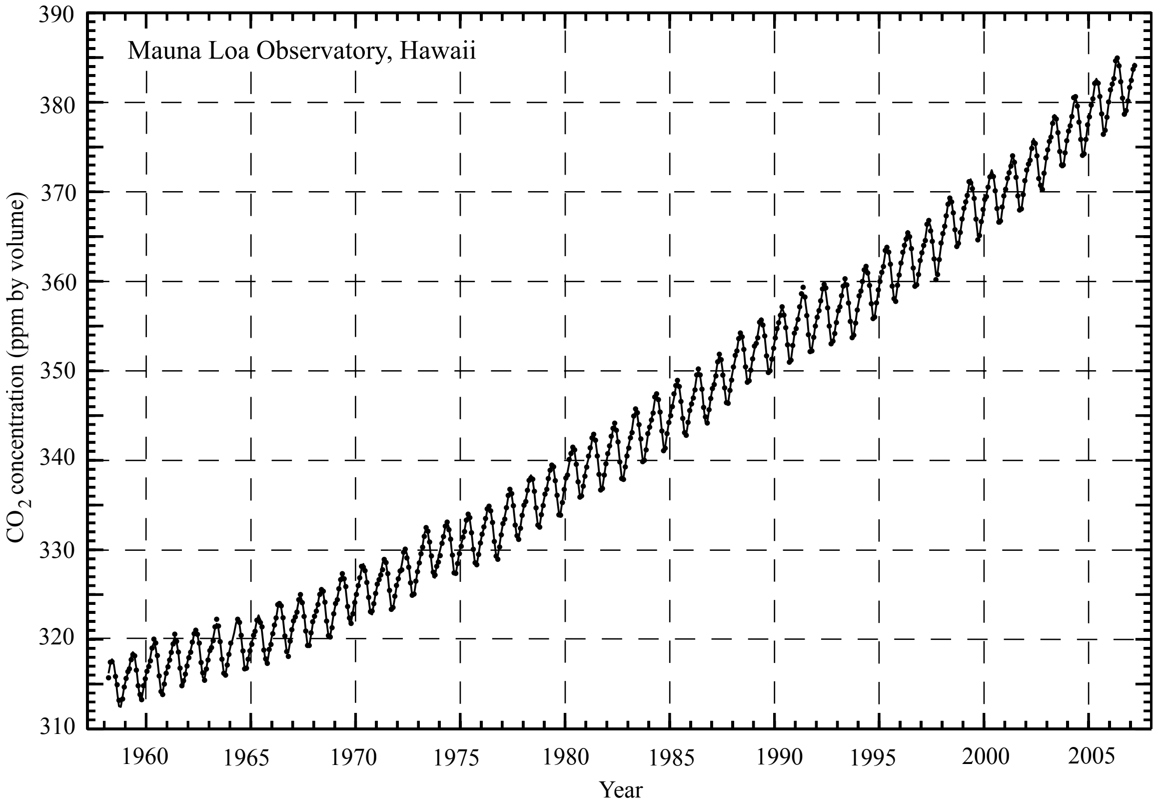


Figure 1.8 Monthly average CO_2 concentration in dry air measured in Hawaii for the indicated year. (Data from: Keeling, C. D. and Whorf, T. P., 2003, Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.)

"photosynthesis" in Figure 1.7 as well as the burning of fossil fuels. The CO_2 increase to the atmosphere is mitigated to some extent by an increased absorption by the ocean. A "biologic pump" in the ocean helps in this removal of CO_2 from the atmosphere. CO_2 is taken up by phytoplankton at the ocean's surface because of reaction [1.2]. When the phytoplankton die, they sink to the deep ocean where they are increasingly unstable and decay by reaction [1.3] and thus transfer CO_2 from shallow to deep water. This then promotes a greater flux of atmospheric CO_2 to the shallow ocean.

To determine the CO_2 concentration in the atmosphere before direct measurements were made the concentration of CO_2 in air trapped in ice can be measured. Those formed from atmospheric precipitation of H_2O in annual layers in the Arctic and Antarctica give some records greater than 10,000 years. Determinations from Siple Station in West Antarctica along with the Keeling curve are given in **Figure 1.9**.

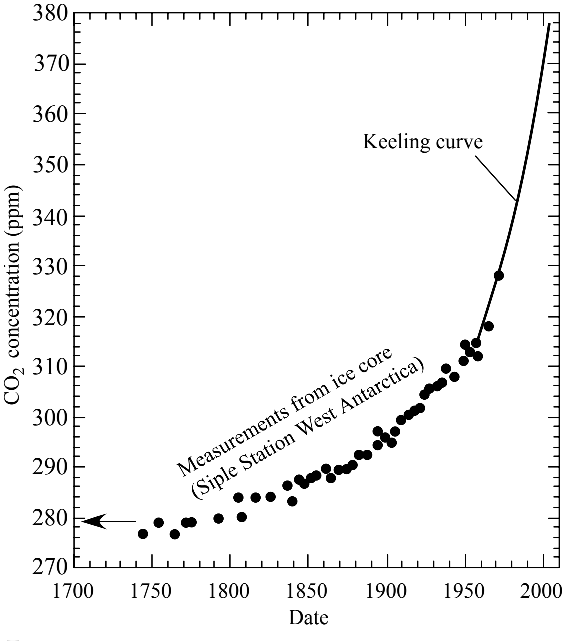


Figure 1.9 Yearly average CO_2 concentration in the atmosphere for the given date from the Keeling curve and ice core determinations. (Data from: Friedli, H., H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, 1986, Ice core record of 13C/12C ratio of atmospheric CO_2 in the past two centuries. *Nature* v. 324, pp. 237–238.)

The increases of concentration of CO_2 with time in the atmosphere outlined in Figures 1.7 and **1.9** can be compared with the increases given in Figure 1.8. From Figure 1.8 the average increase of CO_2 in the atmosphere with time is about 1.55 ppm by volume per year for the past few years. This is determined by measuring the slope of the line connecting points at the same time of year. With the atmosphere modeled as an ideal gas, this ppm by volume increase is equal to its mole fraction increase per year of $1.55 \times 10^{-6}\ \text{yr}^{-1}$. The increase in carbon is then given by this mole fraction times the molecular weight of carbon, $12.01\ \text{g mol}^{-1}$, times the mass of the atmosphere in moles. This molar mass of carbon equals the mass of the atmosphere in grams, 5.3×10^{21} g (Campbell, 1977), divided by the grams of carbon in a mole of air, $28.97\ \text{g mol}^{-1}$ or

$$\frac{1.55 \times 10^{-6}\ \text{yr}^{-1} \times 12.01\ \text{g mol}^{-1} \times 5.3 \times 10^{21}\ \text{g}}{28.97\ \text{g mol}^{-1}} = 3.4\ \text{Pg yr}^{-1}. \qquad [1.4]$$

This is consistent with the value outlined in Table 1-4. Measurements in ice cores from ice layers older than the year 1750 give an atmospheric CO_2 concentration of 280 ± 3 ppm for hundreds of years. Therefore, the increase in atmospheric CO_2 started with the advent of the Industrial Revolution.

Methane Clathrate Stability

An examination of Figure 1.7 indicates the large size of the *methane clathrate* reservoir of carbon containing methane gas, CH_4. Methane in clathrates occurs with bacterial decomposition of organic matter in a low oxygen environment, similar to the formation of "swamp gas." Under low enough temperatures and high enough pressures a solid methane clathrate phase forms in the sediments. Methane clathrates are cage-like structures of cubic ice with a methane gas atom within the cage. In the ocean, methane clathrate is not stable in sediments until the water above reaches a thickness of 1 km. At these depths sediments are cool enough and under high enough pressure.

With increasing depth in the earth, the increasing temperature along the geothermal gradient makes clathrate unstable. As shown in **Figure 1.10**, this occurs about 1/2 km below the ocean floor or at a depth 3/4 km below the land surface.

Because the size of the methane clathrate reservoir is greater than all the carbon residing in other fossil fuel deposits, researchers have investigated the possibility of obtaining methane from clathrates as a potential fuel source. However, the technical problems of large-scale development have been intractable to date. Some investigators have suggested natural large-scale release of methane from clathrates limits the extent of ice ages. Sea level is lowered in an ice age as more water is put on the continents as ice. These investigators argue the lower sea level lowers the pressure put on the methane clathrates at the bottom of the ocean and they become unstable. The clathrates release CH_4 to the atmosphere that reacts with oxygen producing CO_2. As greenhouse gasses, CH_4 and CO_2 cause global warming, which ends the ice age.

Common Rocks

In order to understand the formation of mineral resources it is helpful to have some background with terms used to describe rocks and minerals. Rocks can be classified as igneous, sedimentary, or metamorphic.

Igneous rocks are formed by the crystallization of molten *magma*. A *sedimentary rock* is produced from solid grains that have weathered from material at the earth's surface, then settled and accumulated or they have formed from solid grains that have precipitated directly out of water. *Metamorphic rocks* are previously formed igneous or sedimentary rocks that have changed their appearance by undergoing significant changes in mineralogy, structure, and/or chemistry in response to changes in temperature and/or pressure as they are buried in the earth.

Rocks are made up of minerals, glass, and organic material. There are many minerals of importance. Given in **Table 1.5** are some common rock-forming minerals divided into those that are produced in igneous, sedimentary, and metamorphic processes.

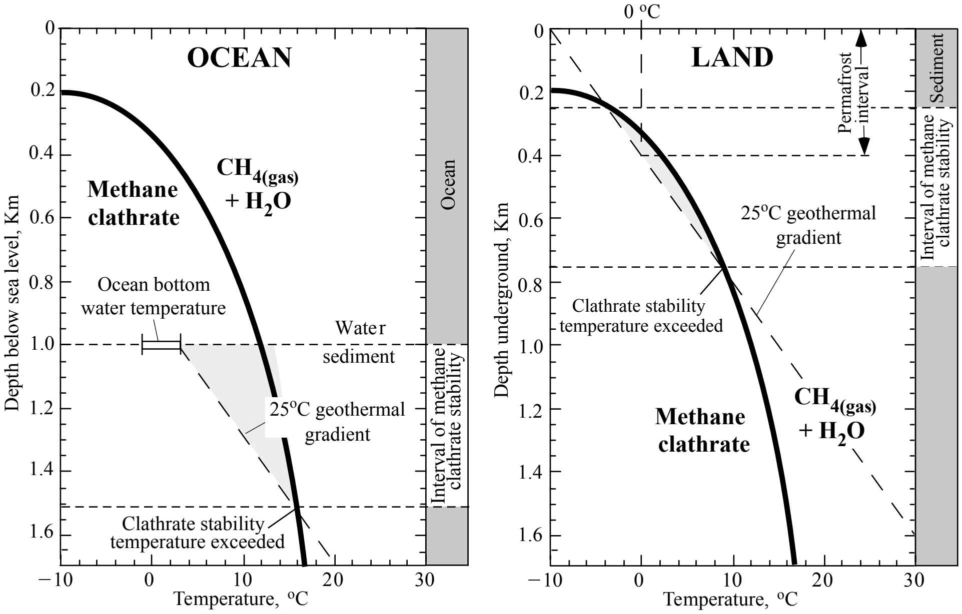


Figure 1.10 Methane-clathrate stability, given by the light grey areas, as a function of temperature and depth both in the ocean and on land.

Table 1.5 COMMON ROCK-FORMING MINERALS.

MINERALS FORMED IN IGNEOUS ROCKS		
MINERAL	**COMPOSITION**	**COLOR**
Quartz	SiO_2	Translucent, white, grey
Feldspar: Plagioclase K-feldspar	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$ $KAlSi_3O_8$	Light to dark in color Typically pink
Hornblende	$Ca_2(Mg,Fe)_4Al(AlSi_7O_{22})(OH)_2$	Black
Pyroxene	$Ca(Mg,Fe)Si_2O_6$ or $(Mg,Fe)_2Si_2O_6$	Green to black
Mica: Muscovite Biotite	$KAl_2(AlSi_3)O_{10}(OH)_2$ $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Translucent Black
Olivine	$(Mg,Fe)_2SiO_4$	Olive green to black
Magnetite	Fe_3O_4	Black, shiny
MINERALS FORMED IN SEDIMENTARY ROCKS		
MINERAL	**COMPOSITION**	**COLOR**
Calcite	$CaCO_3$	Translucent, white
Dolomite	$CaMg(CO_3)_2$	White, grey, pink
Kaolinite	$Al_2Si_2O_5(OH)_4$	White
Halite	NaCl	Translucent
Gypsum	$CaSO_4 \bullet 2H_2O$	Translucent, white
Hematite	Fe_2O_3	Red, shiny grey
Limonite	$FeOOH \bullet nH_2O$	Yellowish red
MINERALS FORMED IN METAMORPHIC ROCKS		
MINERAL	**COMPOSITION**	**COLOR**
Talc	$Mg_3Si_4O_{10}(OH)_2$	White
Chlorite	$Mg_5Al_2Si_3O_{10}(OH)_8$	Green
Garnet	$(Fe,Mg,Ca)_3Al_2Si_3O_{12}$	Pink, red, green, black
Alumino-silicates: Andalusite Kyanite Sillimanite	Al_2SiO_5 Al_2SiO_5 Al_2SiO_5	Often pink Blue to white, grey, green, black Transparent to white

Igneous Rocks

Igneous rock that has formed within the earth is termed plutonic and that crystallized from lavas as well as eruptive gas and airborne magma at the earth's surface is called volcanic. **Figure 1.11** gives the names and mineral content of common volcanic and plutonic igneous rocks. Note that these

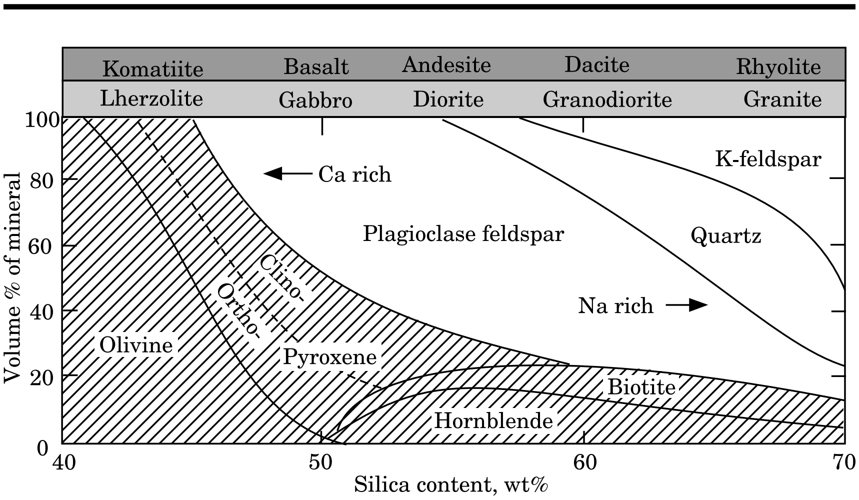


Figure 1.11 Volume percent of minerals in plutonic igneous rocks as a function of their silica content. The lined region of the diagram indicates the mafic (dark-colored) minerals, whereas the unlined area gives the felsic (light-colored) minerals in the rock. The light grey bar on the top of the diagram outlines the name of the intrusive plutonic igneous rock for the indicated range of SiO_2 content. The darker grey bar specifies the equivalent volcanic rocks of similar chemical composition.

common igneous rocks are defined based on their SiO_2 content. Rocks, magma, or minerals that are rich in magnesium and iron are termed *mafic*. They tend to be dark in color. Mafic rocks and magmas have $45\ \text{wt\%} < SiO_2 < 52\ \text{wt\%}$. This includes both basalt and gabbro as shown in Figure 1.11. *Ultramafic* is a term used for rocks and magma with less than 45 wt% SiO_2. They occur much less frequently than mafic rocks in the crust. The upper mantle of the earth is, however, composed of the ultramafic rock peridotite.

Sedimentary Rocks

Sedimentary rocks cover the continental crust to an extensive depth in some locations. However, on a global scale they are a thin veneer over the metamorphic and igneous rocks that make up 95% of the earth's crust. Sedimentary rocks are formed from deposited sediments in layers termed strata that produce beds of rock. A bed is the smallest unit in sedimentary rocks, ranging in thickness from a centimeter to several meters that is distinguishable from beds above and below it. Given in **Table 1.6** are some sedimentary rock names and their characteristics.

Metamorphic Rocks

When rocks, formed at the earth's surface, are buried in the earth they are subjected to higher temperatures and pressures. This is because heat is escaping from the earth. This heat was produced by the conversion of gravitational energy to heat energy when the earth was formed. Added to this is heat produced by radioactive decay of some elements such as radioactive potassium and uranium. As a result, near the earth's surface the increase in temperature with depth, the *geothermal gradient*, is generally between 15° and 40°C per kilometer.

With burial at temperatures of about 150°C and above, sediments and volcanic material produced at the earth's surface undergo notable transformations leading to their recrystallization that are termed metamorphic. Given in **Table 1.7** are names for some metamorphic rocks and their characteristics.

Table 1.6 COMMON SEDIMENTARY ROCKS.

TYPE	PARTICLE SIZE	DESCRIPTION	ROCK NAME
Clastic (Fragments of preexisting rocks)	**Coarse grain**	Round clasts	Conglomerate
		Angular clasts	Breccia
	Fine grain (visible to naked eye)	Predominately quartz and/or feldspar	Sandstone
		Type of sandstone of quartz with >25% K-feldspar	Arkose
		Predominately rock fragments, mica & clay	Graywacke
	Very fine grain (invisible to naked eye)	Some grains can be seen with hand lens	Siltstone
		Grains can't be seen with hand lens, non-laminated	Mudstone
		Grains can't be seen with hand lens, laminated	Shale
Organic	**Varies**	Calcite with or without fossils	Limestone
		Soft, porous carbonaceous plant material	Peat
		Blocky, black carbonaceous plant material	Lignite/Coal
Chemical	Generally, **fine grain**	Composed of dolomite ($CaMg(CO_3)_2$)	Dolostone
		Composed of chalcedony (SiO_2)	Chert
		Composed of halite (NaCl) or gypsum ($CaSO_4 \bullet 2H_2O$)	Evaporite

Table 1.7 COMMON METAMORPHIC ROCKS.

TEXTURE	COMPOSITION	DESCRIPTION	ROCK NAME
Foliated or banded	Pelite (originally clay-rich)	Fine grained with dense, thin pieces	Slate
		Fine grained with satiny luster	Phyllite
		Medium grained with plainer aligned mica	Schist
		Medium-coarse grained, alternating light and dark bands	Gneiss
Non-foliated		Fine grained, dense and dark	Hornfels
	Basalt	Medium-coarse grained, black with prismatic amphibole	Amphibolite
	Carbonate	Medium-coarse grained calcite or dolomite	Marble
	Quartz	Medium-coarse grained quartz	Quartzite
	Organic carbon	Black, shiny, conchoidal fractures	Anthracite

Population Growth

There are two major drivers of increased resource use, population growth, and increased *per capita* use. Estimated past world population as a function of time from 0 AD is given in **Figure 1.12** along with the dates of some historic events. It is estimated that over 55 million people lived in the Eastern and Western Roman Empire at the time the city of Constantinople was built. The *Black Death plague* between 1347 and 1351 likely reduced the population of the world from 450 to 350 million. It is probable that the world population reached 1 billion in about 1810, stood at 2.5 billion in 1950, and increased to over 3 billion by 1960. In 1999 the world population was estimated to be 6 billion, a doubling of the population in less than 40 years.

There were 7 billion people on the earth at the end of 2011. World births have leveled off at about 135 million per year. Deaths are now about 60 million per year resulting in 75 million people added per year. The growth rate of the population is then equal to 75 million people per year/7.0 billion people = 1.07% per year. This 2011 rate of population growth is less than half of its peak of 2.2% per year, which was reached in 1963 (see **Figure 1.13**). A dip in the growth rate in 1959–1960 occurred because of both natural disasters and decreased agricultural output in China due to a massive social reorganization termed the "Great Leap Forward." China's death rate rose sharply and its fertility rate fell by almost half.

Table 1.8 gives the populations and annual growth rates of the world's 20 largest countries. Most of the people in the world live in only a few countries. For instance, in 2009, 37% of the world's population lived in China and India while 22% of the population lived in the next

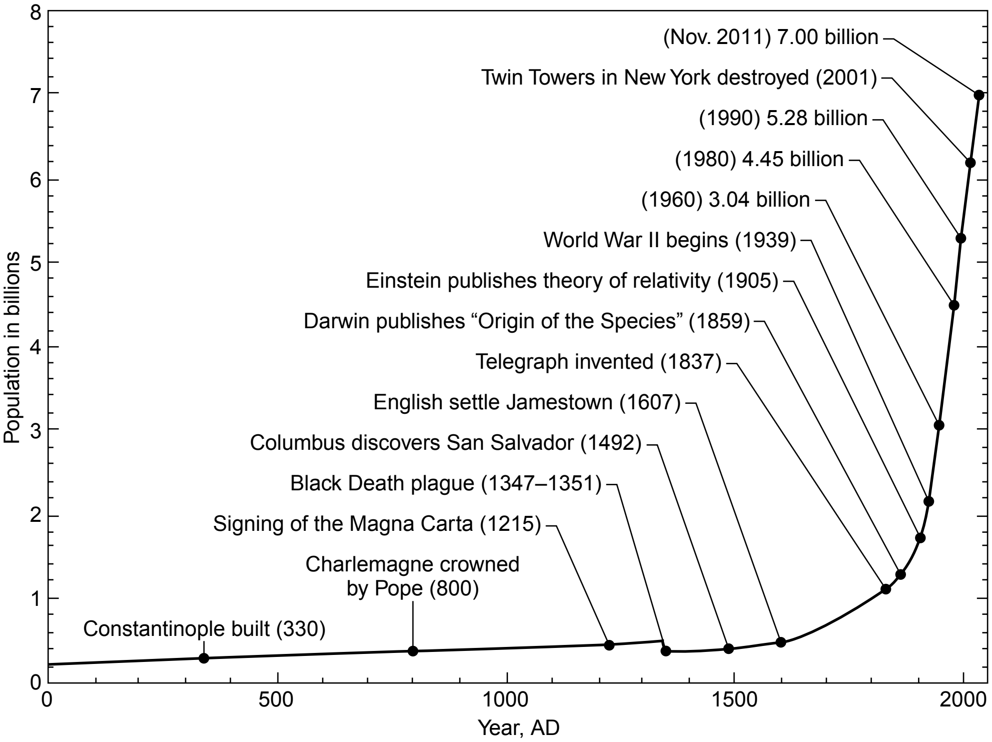


Figure 1.12 World population as a function of time indicating some significant world events.

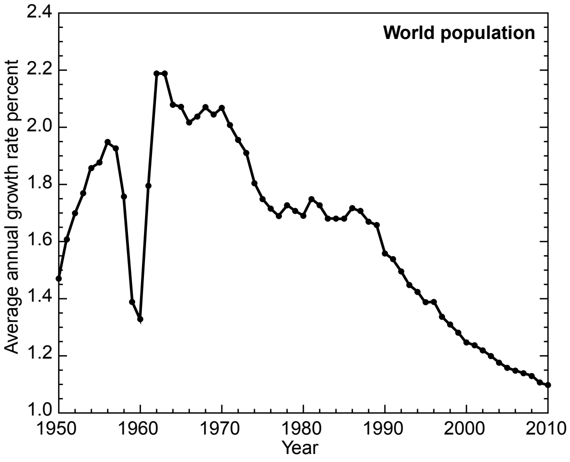


Figure 1.13 Annual mid-year world population growth rate from the U.S. Census Bureau International Data Base (IDS). (Data from: U. S. Census Bureau International Data Base.)

eight largest countries, which in order of decreasing population are the United States, Indonesia, Brazil, Pakistan, Bangladesh, Nigeria, Russian Federation, and Japan. The 230 countries that have populations less than 20 million people contain only 11% of the world's population.

Note in Table 1.8 that Russia and Japan have a negative growth rate so they are decreasing populations as a function of time. The growth rate of India is greater than that of the People's Republic of China so that if rates stayed the same India will become the most populous country in the world. To determine when this will happen consider the mathematics of growth.

Mathematics of Growth

If the annual compounded growth rate stabilizes at 1.1% what is the consequence for world population growth into the future? The equation for compounded (exponential) growth of variable x is

$$\frac{dx}{dt} = \mathrm{k}x \qquad [1.5]$$

where k is a constant, called the growth rate, giving the rate of increase of x with time, t. Consider starting with a population of 6.83 billion in 2010 (year = 0) with a rate of growth of k = 1.1% per year. Rearranging and writing the integral of equation [1.5] for x = *population* gives

$$\int_{6.83\text{ billion}}^{\textit{population at } t} \frac{d(\textit{population})}{\textit{population}} = \int_{\text{year}=0}^{\text{year}=t} \mathrm{k}\,dt. \qquad [1.6]$$

With k = 0.011, performing the integration of both sides of equation [1.6] and evaluating the limits results in

$$\ln(\textit{population}\text{ at }t) - \ln(6.83\text{ billion}) = 0.011t - 0. \qquad [1.7]$$

Taking the exponential of both sides, gives

$$(\textit{population}\text{ at }t) = 6.83\text{ billion} \times e^{0.011t}. \qquad [1.8]$$

The evaluation of equation [1.8] as a function of time to 2110 is shown in **Figure 1.14**. Note that in 100 years of growth the population on the earth is calculated to be 20.5 billion people or a tripling of the present population.

To determine when the countries of the People's Republic of China, with a growth rate of 0.60%, and India, with a growth rate of 1.44%, have the same population, equation [1.8] can be written for each country replacing 6.83 billion with their current populations and equating the populations at a time, t, in the future to give

$$\underbrace{1{,}181{,}263{,}000 \times (e^{0.0144t})}_{\text{India}} = \underbrace{1{,}337{,}700{,}000 \times (e^{0.0060t})}_{\text{Peoples Republic of China}}. \qquad [1.9]$$

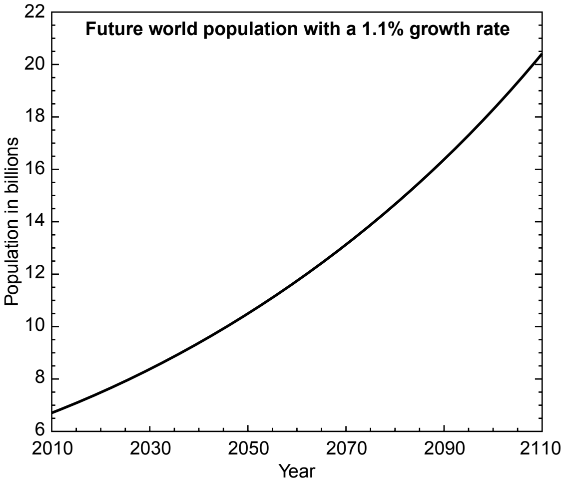


Figure 1.14 Predicted future world population with a 1.1% yearly growth rate as a function of time for the indicated year.

Table 1.8 Population and growth rate range of the 20 largest countries in 2010.

COUNTRY	POPULATION	ANNUAL GROWTH RATE
People's Rep. of China	1,337,700,000	0.58–0.66
India	1,181,263,000	1.41–1.46
United States	309,345,000	0.97–0.98
Indonesia	231,370,000	1.14–1.16
Brazil	192,976,000	1.20–1.26
Pakistan	169,580,000	1.56–1.84
Bangladesh	162,221,000	1.29–1.67
Nigeria	154,729,000	2.00–2.27
Russia	141,927,000	–0.47–0.51
Japan	127,390,000	–0.02–0.19
Mexico	107,551,000	1.12–1.13
Philippines	92,227,000	1.72–1.96
Vietnam	85,790,000	1.14–1.32
Germany	81,758,000	–0.05–0.07
Ethiopia	79,221,000	2.51–3.21
Egypt	78,308,000	1.76–2.03
Iran	74,196,000	0.88–1.35
Turkey	72,561,000	1.26–1.31
Dem Rep. of Congo	66,020,000	2.11–3.22
France	65,447,000	0.49–0.55

Data from: http://en.wikipedia.org/wiki/List_of_countries_by_population.
Annual growth rates from variety of sources.

Taking the natural logarithm of both sides of equation [1.9] and solving for t gives $t = 15$ years. Therefore, in 2025 India will have a greater population than China if the present growth rates stay constant.

Fertility

Humankind presently has an average *fertility rate* of 2.56. The fertility rate is the average number of children a woman will bear in her lifetime. The replacement rate in a population where there is zero population growth (ZPG) is somewhat greater than 2.0 because of a significant infant mortality rate before women are of childbearing age. For the world as a whole it takes a fertility rate of 2.1 to 2.2 to have ZPG. In countries with low life expectancies, the fertility rate for zero population growth is even higher, 2.2 to 3.0. However, even a current fertility rate as low as 2.1 may not ensure zero population growth over time.

If during a particular period of time in the past a population has an unusually large number of children exceeding its ZPG, the added population will pass through their childbearing years increasing the population even if their fertility is 2.1 or less. Most childbearing is done by women between the ages of 15 and 49. If a population has a large number of young people just entering their reproductive years, the rate of growth of that population is sure to rise.

Distribution of People on the Earth as a Function of Time

By 2050, Bangladesh, Ethiopia, and the Democratic Republic of the Congo will be among the 10 most populous countries in the world according to the United Nations Population Division. **Table 1.9** gives estimates of the past world population

Table 1.9 DISTRIBUTION OF THE WORLD'S POPULATION (%) IN MAJOR AREAS ACCORDING TO DIFFERENT MODELS TO 2050.

MAJOR AREA	1950	1975	2009	2050 LOW	2050 MEDIUM	2050 HIGH	2050 CONSTANT
More-developed regions	32.1	25.8	18.1	14.2	13.9	13.8	11.4
Less-developed regions	67.9	74.2	81.9	85.8	86.1	86.2	88.6
Least-developed countries	7.9	8.8	12.2	18.4	18.3	18.1	22.4
Other less-developed countries	60.0	65.4	69.7	67.5	67.8	68.1	66.2
Africa	9.0	10.3	14.8	22.0	21.8	21.7	27.2
Asia	55.5	58.6	60.3	57.0	57.2	57.4	54.5
Europe	21.6	16.6	10.7	7.6	7.6	7.5	6.0
Latin America and Caribbean	6.6	8.0	8.5	7.9	8.0	8.1	7.6
Northern America	6.8	6.0	5.1	5.0	4.9	4.8	4.2
Oceania	0.5	0.5	0.5	0.6	0.6	0.6	0.5

Data from: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2009). *World Population Prospects: The 2008 Revision.*

by region and a prediction for the year 2050. Note that 32% of the population lived in more-developed countries in 1950 but this percentage is decreasing every year and by 2050 is predicted to be somewhere between 14.2% and 13.8%. This is because the population of Africa with its less-developed regions is predicted to grow from 9% of the world population in 1950 to about 22% in 2050.

Figure 1.15 shows the predicted changes in world population by region as a function of time plotted on a logarithmic scale. Note that European population is expected to decrease into the future due to a low birth rate. As given in Table 1.9 the African population is expected to increase rapidly as will the Latin American population. The Latin American population will increase past that in Europe in about the year 2030.

The Demographic Transition

In general, countries become more developed with time. In less-developed countries this development causes a shift from high birth and death rates to low birth and death rates. This is called the *demographic transition*. Slowly declining birth rates following an earlier sharp decline in death rates are today characteristic of most of the less-developed regions of the world. This is due to many factors including the following:

better nutrition,
greater access to medical care,
improved sanitation, and
more widespread immunization.

This decline in death rates with nearly as high a birthrate has caused significant increase in developing nations' populations.

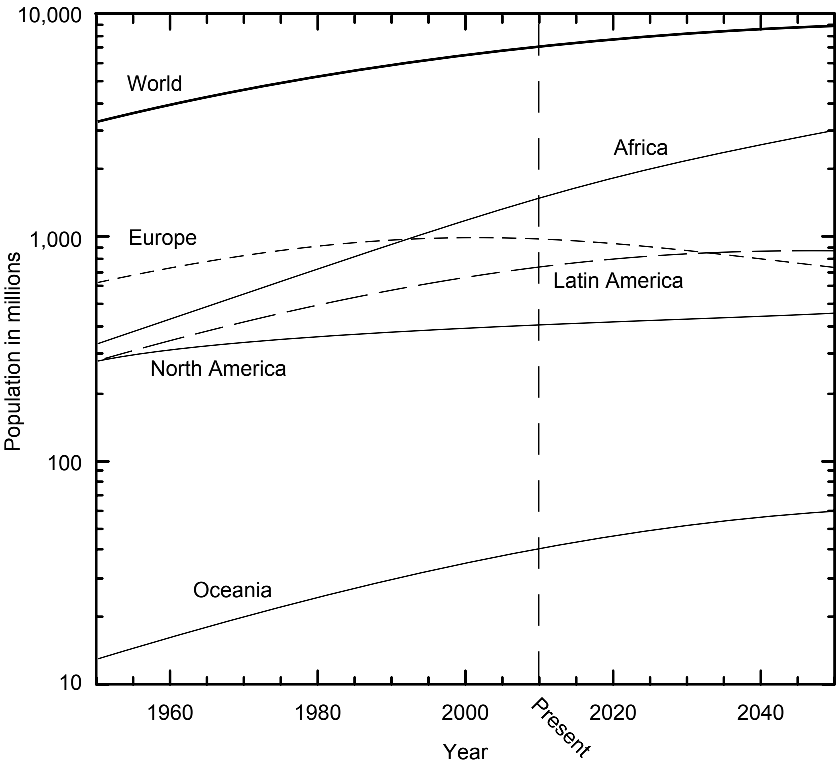


Figure 1.15 Past and estimated future population of the indicated region plotted on a log scale. (Data from: United Nations, Department of Economics and Social Affairs)

Age Distribution of the Human Population

Figure 1.16 gives *population pyramids* for Uganda and Sweden. These indicate the percentage of population in 5-year increments of age for males and females in the country. Uganda with its broad base that rapidly narrows as the population's age increases is characteristic of a population with a high birthrate and high mortality rate in all age groups to age 50 where the relative mortality rate is lower. On the other hand, the barrel-shaped population pyramid for Sweden is characteristic of a low birthrate and low mortality rate population. Variations to the population pyramids point to significant population events. Large permutations in immigration or past high birthrates can lengthen a bar relative to its neighbors. Relative shortening of bars can be the result of war or epidemics that are prevalent in a particular age range of the population.

Figure 1.17 gives population pyramids for China and the United States in terms of total population. China had a classic high birthrate and high mortality rate population distribution like Uganda until 1979 when it instituted a one-child-per-couple policy. Since then the percentage of children has decreased. Note that if the birthrate stabilizes at its current values and the morality rate decreases, a barrel-shaped population distribution given by the 0–14 year groups will develop.

In China population spikes occur in the 40–44 and 20–24 age groups while in the United States the spikes occur at ages of 45–49 and 20–24. The older age spike in population is the *baby boomers*, the demographic boom in births after World War II. This includes those born between 9 months after the war (1946) and 19 years later (1965). This would make them 64 to 45 years old in 2010. Note that the boom in births in China was delayed by about five years from that in the U.S. because of the slower change to a post-war industrial society in China. Baby Boomers are entering their senior years. Many are now retiring and leaving the labor force. With a shrinking working-age population, who will take care of the country's retirees? This is a question that needs to be answered not only in the U.S., but also in the world at large.

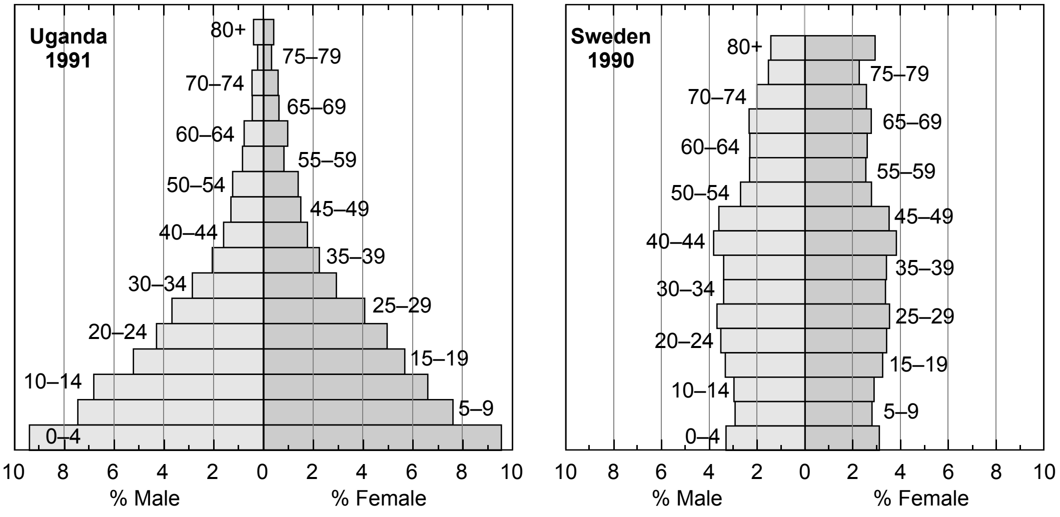


Figure 1.16 Age distribution and male/female ratio of people in Uganda (1991) and Sweden (1990) from U.S. Census Bureau International Data Base. (Data from: U. S. Census Bureau International Data Base.)

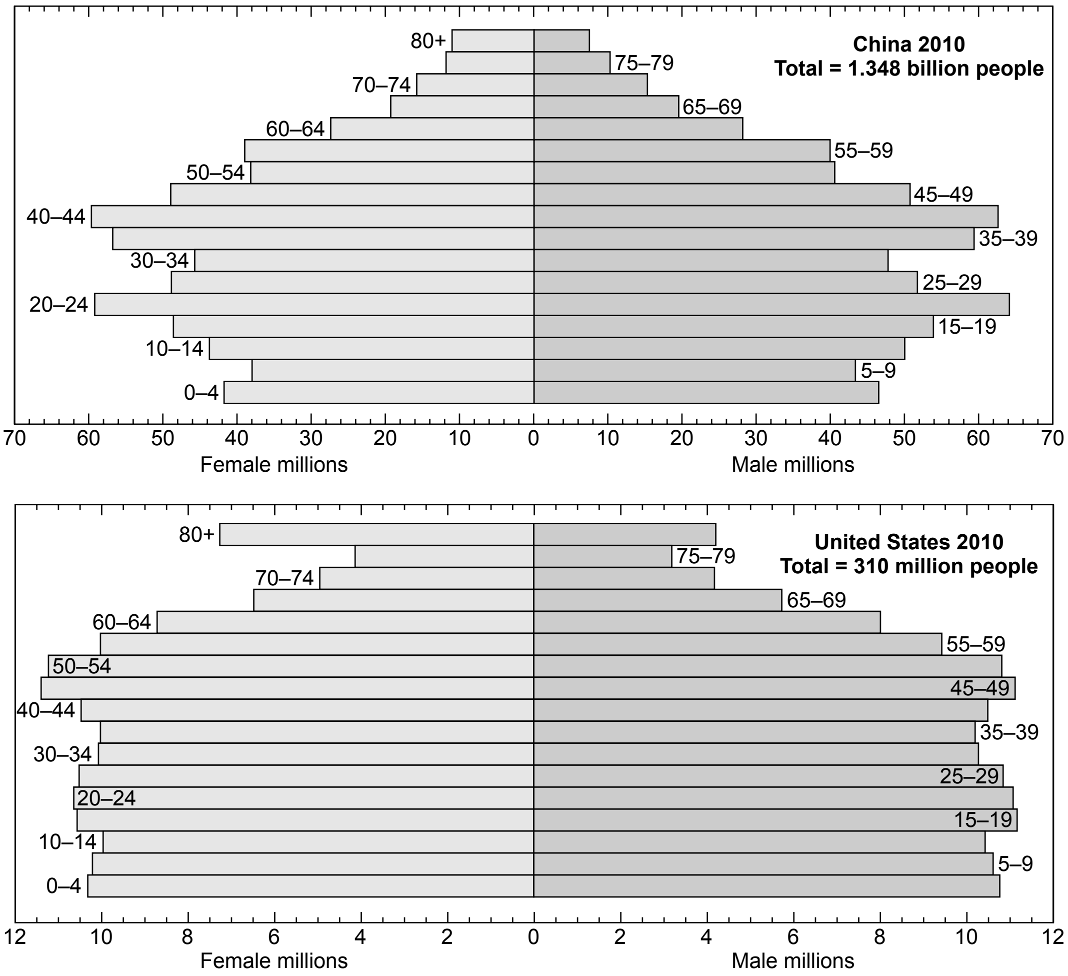


Figure 1.17 Age distribution and male/female ratio in China and the United States in 2010 from data in the U.S. Census Bureau International Data Base. (Data from: U.S. Census Bureau International Data Base.)

The 20–24 age population spike, born between 1990 and 1995 is part of an "Echo Boomer" generation as they are offspring of the Baby Boomers. In the U.S. and Europe they are also referred to as late *Millennials* (or Generation Y, born ~1980–1997) because they were brought up using digital technology and exposed to mass media. Millennials are new voters of which many political parties wish to embrace. In the United States they are the first generation to grow up in a society with both desegregation and sexual equality by law.

The Earth's Human Carrying Capacity

Can the world sustain increased population? A concept developed from population dynamics is the *carrying capacity*. The carrying capacity within a given habitat gives the maximum sustainable abundance of a species in the habitat. When a species population is at its carrying capacity the birth and death rates are equal, and the size of the population does not change with time. Populations that overshoot the carrying capacity are not sustainable, and the environment will adjust to bring the population back to its carrying capacity. In nature, populations vary with time for reasons that may be complex and difficult to understand. The notion of a carrying capacity is useful as it highlights that for all species, including humans, there are habitat limitations to the sizes of populations that can be sustained.

Figure 1.18 shows how a typical species reaches its carrying capacity. When a species is introduced into a habitat its population grows exponentially with time. At some point negative feedbacks such as limits on food or increases in the number of predators slows the increase until the population reaches a steady state, the carrying capacity. The equation for development of a steady-state population is given by

$$\frac{d(population)}{dt} = \mathrm{k} \times population \times \left(\frac{\mathrm{K} - population}{\mathrm{K}}\right) \quad [1.10]$$

where K is the carrying capacity and k is the growth rate as discussed above. Note the similarity of equation [1.10] to equation [1.5] but the right-hand side is multiplied by an added term in parenthesis involving K. Because the population is always less than K, this term is less than 1 and acts as a negative feedback against exponential growth. As the population approaches K the term in parenthesis becomes zero and the steady state of the carrying capacity is reached as the change in population with time is zero. In Figure 1.18 equation [1.10] is plotted as a dashed line with k = 1.1% per time unit (years) and K = 9 billion people.

Given the likely increase in the world population one can ask what the carrying capacity of humans on the earth is? That is, what is the number of people the earth can sustain and what negative feedbacks could limit the population? It has been argued that the earth may be able to support 40 to 50 billion people ~ 3 doublings. However, of the 7 billion people alive today, 0.5 to 1.1 billion are presently undernourished.

Does carrying capacity increase with time because humans have the ability to alter their environment and can make rational choices? It can be argued that humankind will apply advances in

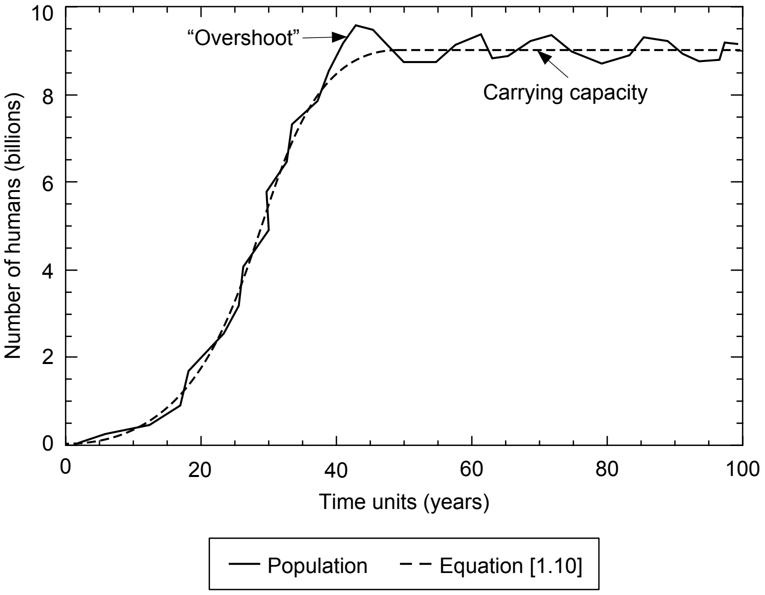


Figure 1.18 A possible model of population growth with time for a system that reaches its carrying capacity plotted as a dashed line as given by equation [1.10] with k = 1.1% and K = 9 billion.

technology and agricultural production techniques to increase the food supply. Also the carrying capacity could increase from improvements in public health and development of vaccines for diseases that decreases the negative feedback in equation [1.10]. Is it possible, however, that humankind will be limited by the resources needed to make these advancements? In the case of humans what could K, the carrying capacity, be controlled by: limited resources of energy, minerals, or fresh water? This text helps one understand the natural resource supplies available to humankind.

In regard to resources, a worldwide *economic stagnation* could occur if we run out of a resource because it is nonrenewable and the world can't satisfy increased demand by substitution or recycling. It could also occur if a resource is renewable but only at a slower rate than required, leading to decreased supply relative to demand. Finally, economic stagnation could occur if problems of pollution and resource degradation occur because industry is free of government intervention (*laissez-faire policy*) leading to world health problems or the inability to obtain available resources, economically. Knowledge of resource availability is required to anticipate these problems.

SUMMARY

Energy is considered in fluxes, an amount per unit area per time. The average flux of energy from the sun at the top of the atmosphere is 1,360 W m^{-2} and from the interior of the earth only 75 *m*W m^{-2}. Both these fluxes are important for resource formation. Resources can be renewable or nonrenewable and their use increases both with population growth and increased per capita use.

Resources such as mineral resources can be classified based on how well their size and concentration are known. Resources are generally considered reserves if they are of high enough concentration to be extracted at current prices and known with reasonable certainty to exist in the earth.

Geochemical cycles are used to characterize the flux of resources through the various reservoirs on the earth. The carbon cycle is not in steady state and more carbon is going into the atmosphere than leaving. It can be shown this increase started in the middle of the eighteenth century and is continuing to the present. Large amounts of methane clathrates exist on the ocean floor and under permafrost. This resource does not appear to be exploitable for its methane gas but if released would lead to extensive global warming.

Rocks are made up of minerals, glass, and organic material. Common rocks contain silicate or carbonate minerals. They are classified as igneous, sedimentary, or metamorphic. Igneous rocks are the most common rock type found in the earth's crust with sedimentary rock occurring on the top of the crust.

World population is growing at about 1.1% per year and with exponential growth will triple the population in 100 years. This is consistent with the world fertility rate, which currently is 2.56. It is not clear what the carrying capacity of the earth with regard to humankind is but the exponential increase is not likely to be sustained much longer.

At their present rates of growth India will surpass China as the world's most populous country in about 2025. A demographic transition occurs as countries develop from high birth and death rate to low birth and death rate. The age distribution in population pyramids of less-developed countries tends to

have a broad base and decreases in number significantly with increasing ages. This is contrasted with developed countries where the number of people in a particular age bracket is similar to the others.

Civilizations have been defined by the resources they use. It appears at present that humankind is making the transformation from the petroleum age to the nuclear plus renewable energy age.

KEY TERMS

baby boomers
Black Death plague
carrying capacity
demographic transition
economic stagnation
energy
fertility rate
flux
fossil fuels
geochemical cycle
geothermal gradient
igneous rock
laissez-faire policy
mafic
magma
metamorphic rock
methane clathrate
metric ton
millennials
per capita
population pyramid
renewable resource
reserve
reserve base
resource
sedimentary rock
steady state
ultramafic
water cycle

PROBLEMS

1. *Working with units of measure*

   The most widely used systems of measurements are S.I. (Systéme International d'Unités) and CGS (Centimetre–Gram–Second) units. Given below in **Table 1.10** and **Table 1.11** are conversion factors between the two systems and some other commonly used units.

   CGS
   dyne = force to accelerate a mass of 1 g by 1 cm s^{-2}

   S.I. (MKS)
   newton = force to accelerate a mass of 1 kg by 1 m s^{-2}

   a. Give a possible unit of both *energy* and *pressure*.
   b. What unit would you have to multiply your pressure unit by to get your energy unit?
   c. If pressure changes on a volume of 10 cm^3 from 10 to 100 bars, how many thermo calories of energy have been added to the volume? How many joules?
   d. How many joules in a barrel of oil?

Table 1.10 Pressure unit conversion factors.

PRESSURE UNIT	BAR	ATMOSPHERE	psi	mm Hg	PASCAL
CGS: 1 μbar = dyne cm^{-2} =	10^{-6}	0.98692×10^{-6}	14.504×10^{-6}	7.50×10^{-4}	0.1
S.I.: 1 pascal = newton m^{-2} =	10^{-5}	0.98692×10^{-5}	14.504×10^{-5}	7.50×10^{-3}	1
1 bar =	1	0.98692	14.504	750.1	10^{5}
1 atmosphere =	1.01325	1	14.696	760	1.01325×10^{5}

Table 1.11 Energy unit conversion factors.

ENERGY UNIT	ERG	JOULE	THERMO CALORIE	cm^3 × BAR	BTU
CGS: 1 erg = dyne cm =	1	10^{-7}	2.3890×10^{-8}	10^{-6}	
S.I.: 1 joule = newton meter =	10^{7}	1	0.23901	10.00	
1 thermo calorie =	4.184×10^{7}	4.1840	1	41.84	3.968×10^{-3}
1 Btu (British thermal unit) =		1055			1
1 Bbl (barrel of oil) =					5.8×10^{6}
1 kWh (kilowatt hour) =		3.6×10^{6}	8.601×10^{5}		3412

2. If the growth rate of a population, P, is 2% per year how long does it take for the population to double? Time to increase by a factor of 10?

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