

The discipline of environmental biophysics relates to the study of energy and mass exchange between living organisms and their environment. The study of environmental biophysics probably began earlier than that of any other science, since knowledge of organism–environment interaction provided a key to survival and progress. Systematic study of the science and recording of experimental results, however, goes back only a few hundred years. Recognition of environmental biophysics as a discipline has occurred just within the past few decades.

Recent progress in environmental biophysics has been mainly in two areas: use of mathematical models to quantify rates of energy and mass transfer and use of conservation principles to analyze mass and energy budgets of living organisms. In quantification of energy and mass transfer rates, environmental biophysicists have followed the lead of classical physics and engineering. There, theoretical and empirical models have been derived that can be applied to many of the transport problems encountered by the design engineer. These same models can be applied to transport processes between living organisms and their surroundings.

This book is written with two objectives in mind. The first is to describe and model the physical microenvironment in which living organisms reside. The second is to present simple models of energy and mass exchange between organisms and their microenvironment with models of organism response to these fluxes of energy and matter. One might consider this a combined science and engineering approach to environmental biology because the intent is to teach the student to calculate actual transfer rates and to understand the principles involved. Numerical examples are presented to illustrate many of the principles, and problems are given at the end of each chapter to help the student develop skill in using the equations. Working the problems should be considered as essential to gaining an understanding of modern environmental biophysics as it is to any course in physics or engineering.

A list of symbols with definitions is provided at the beginning of this book, and tables of data and conversions are in appendices at the end of the book. It would be a good idea to look at those now, and use them frequently as you go through the book. References are given at the end of

each chapter to indicate sources of the materials presented and to provide additional information on subjects that can be treated only briefly in the text. Citations certainly are not intended to be exhaustive, but should lead serious students into the literature.

The effects of the physical environment on behavior and life are such an intimate part of our everyday experience that one may wonder at the need to study them. Heat, cold, wind, and humidity have long been common terms in our language, and we may feel quite comfortable with them. However, we often misinterpret our interaction with our environment and misunderstand the environmental variables themselves. Benjamin Franklin, the early American statesman, inventor, printer, and scientist alludes to the potential for misunderstanding these interactions. In a letter to John Lining, written April 14, 1757 he wrote (Seeger, 1973):

My desk on which I now write, and the lock of my desk, are both exposed to the same temperature of the air, and have therefore the same degree of heat or cold; yet if I lay my hand successively on the wood and on the metal, the latter feels much the coldest, not that it is really so, but being a better conductor, it more readily than the wood takes away and draws into itself the fire that was in my skin.

Franklin's experiment and the analysis he presents help us understand that we do not sense temperature; we sense changes in temperature which are closely related to the flow of heat toward or away from us. The heat flux, or rate of heat flow depends on a temperature difference, but it also depends on the resistance or conductance of the intervening medium.

Careful consideration will indicate that essentially every interaction we have with our surroundings involves energy or mass exchange. Sight is possible because emitted or reflected photons from our surroundings enter the eye and cause photochemical reactions at the retina. Hearing results from the absorption of acoustic energy from our surroundings. Smell involves the flux of gases and aerosols to the olfactory sensors. Numerous other sensations could be listed such as sunburn, heat stress, cold stress, and each involves the flux of something to or from the organism. The steady-state exchange of most forms of matter and energy can be expressed between organisms and their surroundings as:

$$\text{Flux} = g(C_s - C_a) \quad (1.1)$$

where  $C_s$  is the concentration at the organism exchange surface,  $C_a$  is the ambient concentration, and  $g$  is an exchange conductance. As already noted, our senses respond to fluxes but we interpret them in terms of ambient concentrations. Even if the concentration at the organism were constant (generally not the case) our judgment about ambient concentration would always be influenced by the magnitude of the exchange conductance. Franklin's experiment illustrates this nicely. The higher conductance of the metal made it feel colder, even though the wood and the metal were at the same temperature.

## 1.1 Microenvironments

Microenvironments are an intimate part of our everyday life, but we seldom stop to think of them. Our homes, our beds, our cars, the sheltered side of a building, the shade of a tree, an animal's burrow are all examples of microenvironments. The "weather" in these places cannot usually be described by measured and reported weather data. The air temperature may be 10° C and the wind 5 m/s, but an insect, sitting in an animal track sheltered from the wind and exposed to solar radiation may be at a comfortable 25° C. It is the microenvironment that is important when considering organism energy exchange, but descriptions of microclimate are often complicated because the organism influences its microclimate and because microclimates are extremely variable over short distances. Specialized instruments are necessary to measure relevant environmental variables. Variables of concern may be temperature, atmospheric moisture, radiant energy flux density, wind, oxygen and CO<sub>2</sub> concentration, temperature and thermal conductivity of the substrate (floor, ground, etc.), and possibly spectral distribution of radiation. Other microenvironmental variables may be measured for special studies.

We first concern ourselves with a study of the environmental variables—namely, temperature, humidity, wind, and radiation. We then discuss energy and mass exchange, the fundamental link between organisms and their surroundings. Next we apply the principles of energy and mass exchange to a few selected problems in plant, animal, and human environmental biophysics. Finally, we consider some problems in radiation, heat, and water vapor exchange for vegetated surfaces such as crops or forests.

## 1.2 Energy Exchange

The fundamental interaction of biophysical ecology is energy exchange. Energy may be exchanged as stored chemical energy, heat energy, radiant energy, or mechanical energy. Our attention will be focused primarily on the transport of heat and radiation.

Four modes of energy transfer are generally recognized in our common language when we talk of the "hot" sun (radiative exchange) or the "cold" floor tile (conduction), the "chilling" wind (convection), or the "stifling" humidity (reduced latent heat loss). An understanding of the principles behind each of these processes will provide the background needed to determine the physical suitability of a given environment for a particular organism.

The total heat content of a substance is proportional to the total random kinetic energy of its molecules. Heat can flow from one substance to another if the average kinetic energies of the molecules in the two substances are different. Temperature is a measure of the average random kinetic energy of the molecules in a substance. If two substances at different temperatures are in contact with each other, heat is transferred

from the high-temperature substance to the low by conduction, a direct molecular interaction. If you touch a hot stove, your hand is heated by conduction.

Heat transport by a moving fluid is called convection. The heat is first transferred to the fluid by conduction; the bulk fluid motion carries away the heat stored in the fluid. Most home heating systems rely on convection to heat the air and walls of the house.

Unlike convection and conduction, radiative exchange requires no intervening molecules to transfer energy from one surface to another. A surface radiates energy at a rate proportional to the fourth power of its absolute temperature. Both the sun and the earth emit radiation, but because the sun is at a higher temperature the emitted radiant flux density is much higher for the surface of the sun than for the surface of the earth. Much of the heat you receive from a campfire or a stove may be by radiation and your comfort in a room is often more dependent on the amount of radiation you receive from the walls than on the air temperature.

To change from a liquid to a gaseous state at 20° C, water must absorb about 2450 joules per gram (the latent heat of vaporization), almost 600 times the energy required to raise the temperature of one gram of water by one degree. Evaporation of water from an organism, which involves the latent heat required to convert the liquid water to vapor and convection of this vapor away from the organism, can therefore be a very effective mode of energy transfer. Almost everyone has had the experience of stepping out of a swimming pool on a hot day and feeling quite cold until the water dries from their skin.

### 1.3 Mass and Momentum Transport

Organisms in natural environments are subject to forces of wind or water and rely on mass transport to exchange oxygen and carbon dioxide. The force of wind or water on an organism is a manifestation of the transport of momentum from the fluid to the organism. Transport of momentum, oxygen, and carbon dioxide in fluids follow principles similar to those developed for convective heat transfer. Therefore, just one set of principles can be learned and applied to all three areas.

### 1.4 Conservation of Energy and Mass

One of the most powerful laws used in analyzing organism–environment interaction is the conservation law. It states that neither mass nor energy can be created or destroyed by any ordinary means. The application of this law is similar to the reconciliation of your checking account. You compute the deposits and withdrawals, and the difference is the balance or storage. As an example, consider the energy balance of a vegetated surface. We can write an equation representing the inputs, losses, and

storage of energy as:

$$R_n + M - H - \lambda E = G \quad (1.2)$$

Here,  $R_n$  represents the net flux density of radiation absorbed by the surface,  $M$  represents the supply of energy to the surface by metabolism or absorption of energy by photosynthesis,  $H$  is the rate of loss of sensible heat (heat flow by convection or conduction due to a temperature difference),  $\lambda E$  is the rate of latent heat loss from the surface ( $E$  is the rate of evaporation of water and  $\lambda$  is the latent heat of evaporation or the heat absorbed when a gram of water evaporates), and  $G$  is the rate of heat storage in the vegetation and soil. A similar equation could be written for the water balance of a vegetated surface. Since conservation laws cannot be violated, they provide valuable information about the fluxes or storage of energy or mass. In a typical application of Eq. (1.2) we might measure or estimate  $R_n$ ,  $M$ ,  $H$ , and  $G$ , and use the equation to compute  $E$ . Another typical application is based on the fact that  $R_n$ ,  $H$ ,  $E$ , and  $G$  all depend on the temperature of the surface. For some set of environmental conditions (air temperature, solar radiation, vapor pressure) there exists only one surface temperature that will balance Eq. (1.2). We use the energy budget to find that temperature.

### 1.5 Continuity in the Biosphere

The biosphere, which is where plants and animals live within the soil and atmospheric environments, can be thought of as a continuum of spatial scales and system components. A continuum of gas (air, water vapor, carbon dioxide, oxygen, etc.) exists from the free atmosphere to the air spaces within the soil and even the air spaces within leaves. A continuum of liquid water exists from pores within a wet soil to cells within a plant root or leaf. Throughout the system the interfaces between liquid and gas phases are the regions where water molecules go from one state to another, and these regions are where latent heat exchanges will occur. These latent heat exchanges provide a coupling between mass exchanges of water and energy exchanges. The soil is obviously linked to the atmosphere by conduction and diffusion through pores, but it is also linked to the atmosphere through the plant vascular system.

Energy and mass conservation principles can be applied to this entire system or to specific components such as a single plant, leaf, xylem vessel, or even a single cell. The transport equations can also be applied to the entire system or to a single component. Clearly, one must define carefully what portion of the system is of interest in a particular analysis.

Animals may be components of this system from microscopic organisms in films of water in the soil to larger fauna such as worms, or animals on leaves such as mites or grasshoppers, or yet larger animals in the canopy space. The particular microenvironment that the animal is exposed to will depend on interactions among components of this continuum. Animals,



model. As Albert Einstein is purported to have said: "Everything should be made as simple as possible, but not simpler."

The relation between the spatial scale of some desired prediction or understanding and the scale of heterogeneity inherent in the system is essential to the process of simplification. Materials in nature tend to be heterogeneous, not pure. One of the distinguishing features of human activity is the tendency to categorize nature into its elements, purify the naturally occurring mixtures, and reassemble the pure elements into new arrangements. In nature, homogeneous materials, which are materials with uniform properties throughout their volumes, tend to be rare. Obviously, if we go to fine enough scale, nothing is homogeneous; therefore homogeneity depends on spatial scale. In environmental biophysics we consider natural materials such as soil, rock layers, vegetation mixtures, and animal coats. The principles that are commonly used in environmental biophysics are most easily understood and used with pure materials. Therefore a key aspect of environmental biophysics is knowing when assumptions of homogeneity are adequate, and when a meaningful solution to a problem requires some level of treatment of heterogeneity. Most often we treat natural media as homogeneous but assign properties that preserve the major influence of known heterogeneity.

Consider a soil, which consists of a mineral matrix made up of particles of various sizes and characteristics, with organic matter at various stages of decomposition, air, water, plant roots, worms, insects, fungi, bacteria, etc. Soil certainly is a heterogeneous medium. However, we can simulate heat transport on the scale of meters quite well by assuming soil to be homogeneous with a thermal conductivity that depends on water content, particle type and size distribution, and density. In the case of soil, the heterogeneity usually is small (millimeters) compared to the scale on which we desire to predict heat flow (meters). However, if we wish to predict the temperature and moisture environments beneath individual rocks on the surface of the soil because that is where some organism lives, then we have to deal with the apparent heterogeneity by using more complex descriptions. In the case of this heterogeneous material called "soil," various bulk properties are defined such as bulk density, heat capacity, air permeability, capillary conductivity, etc.

A second heterogeneous natural system of interest to us is a plant canopy, which consists of leaves, branches, stems, fruits, and flowers all displayed with elegance throughout some volume and able to move in response to wind, heliotropism, growth, or water stress. Simple equations have been used quite successfully to describe light penetration and canopy photosynthesis by assuming the canopy to behave like a homogeneous green slime. In spite of the seeming inappropriateness of describing photosynthesis of a 50 m tall forest canopy by radiation penetration through a green slime, a convincing intuitive argument can be forged using geometry and statistics of random distributions that is supported by direct field measurements. In fact, statistics is one of the means used to appropri-

ately average over heterogeneity to define properties of a representative homogeneous substitute.

## 1.7 Applications

From the examples already given, it is quite obvious that environmental biophysics can be applied to a broad spectrum of problems. Fairly complete evaluations already exist for some problems, though much work remains to be done. Analysis of human comfort and survival in hot and cold climates requires a good understanding of the principles we will discuss. Preferred climates, survival, and food requirements of domestic and wild animals can also be considered. Plant adaptations in natural systems can be understood, and optimum plant types and growing conditions in agriculture and forestry can be selected through proper application of these principles. Even the successful architectural design of a building, which makes maximum use of solar heat and takes into account wind and other climatological variables, requires an understanding of this subject. Finally, models that forecast the weather or predict changes in past and future climates rely heavily on the principles of environmental biophysics to accommodate exchanges between the surface of the earth and the atmosphere.

As we study environmental biophysics, we will find that people from "primitive" cultures, and even animals, often have a far better understanding of the application of its principles than we do. Understanding the environment and how best to interact with it often makes the difference between life and death for them, whereas for us it may just mean a minor annoyance or an increased fuel bill.

## 1.8 Units

Units consistent with the Systeme International (SI) will be used in this book. The SI base units and their accepted symbols are the meter (m) for length, the kilogram (kg) for mass, the second (s) for time, the Kelvin (K) for thermodynamic temperature, and the mole (mol) for the amount of substance. Units derived from these, which we use in this book are given in Table 1.1. Additional derived units can be found in Page and Vigoureux (1974).

The Celsius temperature scale is more convenient for some biophysical problems than the thermodynamic (Kelvin) scale. We will use both. By definition  $C = K - 273.15$ . Since the Celsius degree is the same size as the Kelvin degree, derived units with temperature in the denominator can be written as either  $C^{-1}$  or  $K^{-1}$ . For example, units for specific heat are either  $J kg^{-1} C^{-1}$  or  $J kg^{-1} K^{-1}$ . To distinguish between the two temperature scales, we will use T in standard font for Celsius temperature, and in bold font (**T**) for Kelvin temperature. Some useful factors for converting to SI units can be found in Table A.4 in the Appendix.

heliotropism: an involuntary orientation  
response by an organism in response

Mistake

Mistake

Mistake

need defining mistake

TABLE 1.1. Examples of derived SI units and their symbols.

| Quantity            | Name   | Symbol | SI base units                                  | Derived Units                      |
|---------------------|--------|--------|--|------------------------------------|
| area                | —      | —      | m <sup>2</sup>                                 | —                                  |
| volume              | —      | —      | m <sup>3</sup>                                 | —                                  |
| velocity            | —      | —      | m s <sup>-1</sup>                              | —                                  |
| density             | —      | —      | kg m <sup>-3</sup>                             | —                                  |
| force               | Newton | N      | m kg s <sup>-2</sup>                           | —                                  |
| pressure-force/area | Pascal | Pa     | kg m <sup>-1</sup> s <sup>-2</sup>             | N m <sup>-2</sup>                  |
| energy              | joule  | J      | m <sup>2</sup> kg s <sup>-2</sup>              | N m                                |
| chemical potential  | —      | —      | m <sup>2</sup> s <sup>-2</sup>                 | J kg <sup>-1</sup>                 |
| power               | watt   | W      | m <sup>2</sup> kg s <sup>-3</sup>              | J s <sup>-1</sup>                  |
| concentration       | —      | —      | mol  | —                                  |
| mol flux density    | —      | —      | mol m <sup>-2</sup> s <sup>-1</sup>            | —                                  |
| heat flux density   | —      | —      | kg s <sup>-3</sup>                             | W m <sup>-2</sup>                  |
| specific heat       | —      | —      | m <sup>2</sup> s <sup>-2</sup> K <sup>-1</sup> | J kg <sup>-1</sup> K <sup>-1</sup> |

TABLE 1.2. Accepted SI prefixed and symbols for multiples and submultiples of units.

| Multiplication Factor                       | Prefix | Symbol |
|---|--------|--------|
| 1 000 000 000 000 000 000=10 <sup>18</sup>  | exa    | E      |
| 1 000 000 000 000 000=10 <sup>15</sup>      | peta   | P      |
| 1 000 000 000 000=10 <sup>12</sup>          | tera   | T      |
| 1 000 000 000=10 <sup>9</sup>               | giga   | G      |
| 1 000 000=10 <sup>6</sup>                   | mega   | M      |
| 1 000=10 <sup>3</sup>                       | kilo   | k      |
| 100=10 <sup>2</sup>                         | hecto  | h      |
| 10=10 <sup>1</sup>                          | deka   | da     |
| 0.1=10 <sup>-1</sup>                        | deci   | d      |
| 0.01=10 <sup>-2</sup>                       | centi  | c      |
| 0.001=10 <sup>-3</sup>                      | milli  | m      |
| 0.000 001=10 <sup>-6</sup>                  | micro  | μ      |
| 0.000 000 001=10 <sup>-9</sup>              | nano   | n      |
| 0.000 000 000 001=10 <sup>-12</sup>         | pico   | p      |
| 0.000 000 000 000 001=10 <sup>-15</sup>     | femto  | f      |
| 0.000 000 000 000 000 001=10 <sup>-18</sup> | atto   | a      |

To make the numbers used with these units convenient, prefixes are attached indicating decimal multiples of the units. Accepted prefixes, symbols, and multiples are shown in Table 1.2. The use of prefix steps smaller than 10<sup>3</sup> is discouraged. We will make an exception in the use of the cm, since mm is too small to conveniently describe the sizes of things like leaves, and m is too large. Prefixes can be used with base units or derived units, but may not be used on units in the denominator of a derived unit (e.g., g/m<sup>3</sup> or mg/m<sup>3</sup> but not mg/cm<sup>3</sup>). The one exception to this rule that we make is the use of kg, which may occur in the denominator because it is the fundamental mass unit. Note in Table 1.2 that powers of ten are often used to write very large or very small numbers. For example, the number 0.0074 can be written as 7.4 × 10<sup>-3</sup> or 86400 can be written as 8.64 × 10<sup>4</sup>.

Most of the numbers we use have associated units. Before doing any computations with these numbers, it is important to convert the units to base SI units, and to convert the numbers using the appropriate multiplier from Table 1.2. It is also extremely important to write the units with the associated numbers. The units can be manipulated just as the numbers are, using the rules of multiplication and division. The quantities, as well as the units, on two sides of an equation must balance. One of the most useful checks on the accuracy of an equation in physics or engineering is the check to see that units balance. A couple of examples may help to make this clear.

**Example 1.1.** The energy content of a popular breakfast cereal is 3.9 kcal/g. Convert this value to SI units (J/kg).

**Solution.** Table A.4 gives the conversion, 1 J = 0.2388 cal so

$$\frac{3.9 \text{ kcal}}{\text{g}} \times \frac{10^3 \text{ cal}}{\text{kcal}} \times \frac{10^3 \text{ g}}{\text{kg}} \times \frac{1 \text{ J}}{0.2388 \text{ cal}} = 16.3 \times 10^6 \frac{\text{J}}{\text{kg}} = 16.3 \text{ MJ/kg.}$$

**Example 1.2.** Chapter 2 gives a formula for computing the damping depth of temperature fluctuations in soil as  $D = \sqrt{\frac{2\kappa}{\omega}}$ , where  $\kappa$  is the thermal diffusivity of the soil and  $\omega$  is the angular frequency of temperature fluctuations at the surface. Figure 8.4 shows that a typical diffusivity for soil is around 0.4 mm<sup>2</sup>/s. Find the diurnal damping depth.

**Solution.** The angular frequency is  $2\pi/P$ , where  $P$  is the period of temperature fluctuations. For diurnal variations, the period is one day (see Chs. 2 & 8 for more details) so  $\omega = 2\pi/1 \text{ day}$ . Converting  $\omega$  and  $\kappa$  to SI base units gives:

$$\omega = \frac{2\pi}{1 \text{ day}} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ s}} = 7.3 \times 10^{-5} \text{ s}^{-1}$$

$$\kappa = \frac{0.4 \text{ mm}^2}{\text{s}} \times \frac{1 \text{ m}}{1000 \text{ mm}} \times \frac{1 \text{ m}}{1000 \text{ mm}} = 4 \times 10^{-7} \text{ m}^2/\text{s}$$

$$D = \sqrt{\frac{2 \times 4 \times 10^{-7} \text{ m}^2\text{s}^{-1}}{7.3 \times 10^{-5} \text{ s}^{-1}}} = 0.1 \text{ m}$$

**Example 1.3.** Units for water potential are J/kg (see Ch. 4). The gravitational component of water potential is calculated from  $\psi_g = -gz$  where  $g$  is the gravitational constant ( $9.8 \text{ ms}^{-2}$ ) and  $z$  is height (m) above a reference plane. Reconcile the units on the two sides of the equation.

**Solution.** Note from Table 1.1 that base units for the joule are  $\text{kg m}^2 \text{ s}^{-2}$  so

$$\frac{\text{J}}{\text{kg}} = \frac{\text{kg m}^2 \text{ s}^{-2}}{\text{kg}} = \frac{\text{m}^2}{\text{s}^2}.$$

The units for the product,  $gz$  are therefore the same as the units for  $\psi$ .

Confusion with units is minimized if the numbers which appear within mathematical operators ( $\sqrt{\quad}$ ,  $\exp$ ,  $\ln$ ,  $\sin$ ,  $\cos$ ,  $\tan$ , etc.) are dimensionless. In most cases we eliminate units within operators, but with some empirical equations it is most convenient to retain units within the operator. In these cases, particular care must be given to specifying the units of the equation parameters and the result. For example, in Ch. 7 we compute the thermal boundary layer resistance of a flat surface from

$$r_{Ha} = 7.4 \sqrt{\frac{d}{u}} \quad (1.3)$$

where  $d$  is the length of the surface in m,  $u$  is the wind speed across the surface in m/s, and  $r_{Ha}$  is the boundary layer resistance in  $\text{m}^2 \text{ s/mol}$ . The constant 7.4 is the numerical result of evaluating numerous coefficients that can reasonably be represented by constant values. The constant has units of  $\text{m}^2 \text{ s}^{1/2}/\text{mol}$ , but this is not readily apparent from the equation. If one were to rigorously cancel units in Eq. (1.3) without realizing that the 7.4 constant has units, the result would appear to be an incorrect set of units for resistance. It would be a more serious matter if  $d$  were entered, for example, in mm, or  $u$  in cm/s, since then the result would be wrong.

\* Whenever empirical equations like Eq. (1.3) are used in this book, we assume that parameters ( $u$  and  $d$  in the equation) are in SI base units, and we will specify the units of the result. This should avoid any ambiguity.

One other source of confusion can arise when units appear to cancel, leaving a number apparently dimensionless, but the units remain important to interpretation and use of the number. For example, the water content of a material might be reported as 0.29, or 29%. However, a water content of  $0.29 \text{ m}^3/\text{m}^3$  can be quite different from a water content of  $0.29 \text{ kg/kg}$ . This type of confusion can always be eliminated by stating the units, even when they appear to cancel. In this book we use mole fraction, or mol/mol to express gas concentration. These units, though appearing to cancel, really represent moles of the particular gas, say water vapor, per mole of air. We therefore retain the mol/mol units with the numbers. It is often helpful to write out mol  $\text{H}_2\text{O}$  or mol air so that one is not tempted to cancel units which should not be canceled. This notation, however, tends to become cumbersome, and therefore is generally not used in the book.

## References

- Page, C.H. and P. Vigoureux (1974) The International System of Units, Nat. Bur. Stand. Spec. Publ. 330 U.S. Govt. Printing Office, Washington, D.C.
- Seeger, R.J. (1973) Benjamin Franklin, New World Physicist, New York: Pergamon Press.

## Problems

- 1.1. Explain why a concrete floor feels colder to you than a carpeted floor, even though both are at the same temperature. Would a snake or cockroach (both poikilotherms) arrive at the same conclusion you do about which floor feels colder?
- 1.2. In what ways (there are four) is energy transferred between living organisms and their surroundings? Give a description of the physical process responsible for each, and an example of each.
- 1.3. Convert the following to SI base units: 300 km, 5 hours,  $0.4 \text{ mm}^2/\text{s}$ , 25 kPa, 30 cm/s, and 2 mm/min.
- 1.4. In the previous edition of this book, and in much of the older literature, boundary layer resistances were expressed in units of s/m. The units we will use are  $\text{m}^2 \text{ s/mol}$ . To convert the old units to the new ones, divide them by the molar density of air ( $41.65 \text{ mol m}^{-3}$  at  $20^\circ \text{C}$  and 101 kPa). If boundary layer resistance is reported to be 250 s/m, what is it in  $\text{m}^2 \text{ s/mol}$ ? What is the value of the constant in Eq. (1.3) if the result is to be in s/m?