biota might contain no ecological niches fit for multicellular individuals at all. Thus all those species would irreversibly vanish from the face of the Earth, so in that sense such a catastrophe would not in any way differ from a complete extinction of life for mobile animals and man.

Therefore preserving the natural communities and the existing species of living beings to the extent necessary to satisfy the Le Chatelier principle with respect to global perturbations of the environment, is the principal condition for further life on the planet. To do that it is necessary to preserve the virgin nature of most of the territory of the planet Earth, rather than conserving the biodiversity in gene banks, reservations, and zoos of negligible surface area (Riviere and Marton-Lefevre, 1992). It is necessary to raise the questions of organizing whole reserved continents and oceans. The first step in that direction might be preserving the continent of Antarctica intact, as is being widely discussed all over the world.

Appendix A
Details of Calculations in Sect. 4.11

Consider in detail the task of calculating the increment in production of the dissolved organic carbon (Gorshkov, 1991b, 1993a). Concentrations of radiocarbon vary at an approximately constant gradient from the surface (s) to depth L, less than 1 km, and then at deeper levels (d) remain approximately constant down to the very seabed at depth H. We denote all the surface preindustrial values by the additional subscript "0". Denoting the concentration of isotope $^{\nu}C$ by the same symbol in italics (and indicating additionally its localization in brackets in either the organic (+) or inorganic (–) reservoir, e.g. $^{\nu}C(s_0^+)$ or $^{\nu}C(d^-)$), we arrive at the following equation of mass budget for carbon (either "+" or "–") in the oceanic column of unit area and depth H:

$$H\frac{d\,^{\nu}C(d)}{dt} = {}^{\nu}F - \frac{^{\nu}C(d)H}{^{\nu}T}, \tag{A.1}$$

where $^{\nu}F$ is the influx to that reservoir column, $^{\nu}T$ is the residence time for atoms of carbon isotope $^{\nu}C$ in the reservoir. The mass of carbon in the oceanic column is assumed equal to $^{\nu}C(d)H$. Deviation of preindustrial concentration in the surface layer from its value at depths influences the total mass of carbon by only several per cent, see Fig. 4.4.

The influx channel to reservoirs of both organic and inorganic carbon is the same for both ^{12}C and ^{14}C. However, ^{14}C has an additional escape channel from each reservoir, the decay channel. The last term in Eq. (A.1) for ^{14}C actually is a sum of two terms:

$$^{14}C(d)H(^{12}T^{-1} + T_c^{-1}),$$

and the residence time for ^{14}C in the reservoir is determined by the well-known relationship for any two parallel channels:

$$\tau^{-1} = T^{-1} + 1, \quad \tau \equiv {}^{14}T/T_c, \quad T \equiv {}^{12}T/T_c, \tag{A.2}$$

where $T_c = 8267$ years is the average lifetime of ^{14}C (Degens et al., 1984).

The influx $^{\nu}F$ in both organic and inorganic reservoirs is proportional to surface water concentration of inorganic radiocarbon $^{\nu}C(s^-)$. The equation $d\,^{\nu}C/dt = 0$ had held for the stationary preindustrial steady state, and the influxes $^{\nu}F_0$ into the reservoir coincided with the escape fluxes from the reservoir:

$$^{\nu}F_0 = {}^{\nu}C(s_0^-)\,^{\nu}v, \tag{A.3}$$

$$^{\nu}F_0 = {}^{\nu}C(d)H/{}^{\nu}T_0. \tag{A.4}$$

Here $^{\nu}v$ is the proportionality coefficient. The flux ratio, $^{14}F_0^{\pm}/{}^{12}F_0^{\pm}$ is equal to the concentration ratio, $^{14}C/{}^{12}C = {}^{14}R(s_0^-)$ in the "s_0^-" range with the accuracy of isotopic fraction corrections of the order of several percent ($^{14}v = {}^{12}v$). Certain chemical reactions take place there, so that carbon is channelled to both the organic and inorganic reservoirs from the dissolved gas (CO_2). We have from (A.2)–(A.4) for both the "+" and "−" reservoirs:

$$\frac{\tau_0}{T_0} = \frac{^{14}R(d)}{^{14}R(s_0^-)} = \frac{\Delta^{14}\mathrm{C}(d)+1}{\Delta^{14}\mathrm{C}(s_0^-)+1}, \tag{A.5}$$

$$\Delta\,^{14}\mathrm{C}(x) \equiv \frac{^{14}R(x)}{^{14}R(a_0)} - 1, \tag{A.6}$$

where $^{14}R(x)$ and $^{14}R(a_0)$ are the $^{14}\mathrm{C}/^{12}\mathrm{C}$ ratios for a single reservoir (+ or −) in the observed region, x, and at the initial time moment, a_0, respectively. At that moment the reservoir was in equilibrium with the preindustrial atmosphere. The value of $\Delta\,^{14}\mathrm{C}$, Eq. (A.6), does not depend on the nature of the reservoir, and is exclusively determined by the age of radiocarbon:

$$\Delta\,^{14}\mathrm{C} = \exp\left(-\frac{t}{T_c}\right) - 1 \quad \text{or} \quad \frac{t}{T_c} = -\ln(1+\Delta\,^{14}\mathrm{C}). \tag{A.7}$$

The ratio ^{14}R in any given sample is usually compared to the same ratio $^{14}R^A$ in a certain standard (a standard reservoir). Using that symbol:

$$\delta\,^{14}\mathrm{C}(x) = \frac{^{14}R(x)}{^{14}R^A} - 1 \tag{A.8}$$

we retrieve the following expression from (A.5) and (A.6) (see Stuiver and Pollach, 1977):

$$\begin{aligned}\Delta\,^{14}\mathrm{C}(x) &= \frac{1+\delta^{14}\mathrm{C}(x)}{1+\delta^{14}\mathrm{C}(a_0)} - 1 \\ &= \delta^{14}\mathrm{C}(x) - 2\left(\delta\,^{13}\mathrm{C}(x) - \delta\,^{13}\mathrm{C}^A\right)(1+\delta\,^{14}\mathrm{C}(x));\end{aligned} \tag{A.9}$$

$$\delta\,^{14}\mathrm{C}(a_0) = 2\left(\delta\,^{13}\mathrm{C}(x) - \delta\,^{13}\mathrm{C}^A\right), \qquad \delta\,^{13}\mathrm{C}(x) = \frac{^{13}R(x)}{^{13}R^S} - 1. \tag{A.10}$$

It is assumed here that isotopic fractionation is controlled by the difference in isotope masses. Then the value of $\delta\,^{14}\mathrm{C}(a_0)$ is twice as large as that of $\delta\,^{13}\mathrm{C}(a_0)$. The isotope $^{13}\mathrm{C}$ is stable, so that $\delta\,^{13}\mathrm{C}(a_0) = \delta\,^{13}\mathrm{C}(x)$. The standard samples A and S for isotopes $^{14}\mathrm{C}$ and $^{13}\mathrm{C}$ differ from each other. That is why $\delta\,^{13}\mathrm{C}^A$ is subtracted from $\delta\,^{13}\mathrm{C}$. Equation (A.9) is true to the accuracy of terms quadratic in $\delta\,^{14}\mathrm{C}(a_0)$ and $\delta\,^{13}\mathrm{C}(x)$. (The value of $\delta\,^{14}\mathrm{C}(x)$ may be close to −1.) To simplify our expressions we use the following notation below:

$$\Delta\,^{14}\mathrm{C}(x) \equiv \Delta(x). \tag{A.11}$$

The values $\Delta(s^{\pm})$ and $\Delta(d^{\pm})$ are borrowed from Druffel and Williams (1990) and $\Delta(s_0^-)$ from Druffel and Suess (1983), and Gorshkov et al. (1990). Generating the ratio $^{14}F_0/{}^{12}F_0$ in (A.4) and using (A.2), (A.5), (A.6), and (A.11) we obtain:

$$\tau_0^{\pm} \equiv \frac{^{14}T^{\pm}}{T_c} = \frac{\Delta(s_0^-) - \Delta(d^{\pm})}{1+\Delta(s_0^-)}; \quad T^{\pm} = \frac{^{12}T^{\pm}}{T_c} = \frac{\Delta(s_0^-) - \Delta(d^{\pm})}{1+\Delta(d^{\pm})}. \tag{A.12}$$

Using (A.11) and (A.12) we have:

$$\Delta(s_0^-) = -0.05, \quad \Delta(d^-) = -0.23, \quad \Delta(s^-) = 0.13, \quad \Delta(d^+) = -0.53, \tag{A.13}$$

$$\Delta(s^+) = -0.18; \quad \tau^+ = 0.51, \quad T^+ = 1.02, \quad \tau^- = 0.19, \quad T^- = 0.23.$$

Note that the residence time T coincides with the age t at low $\Delta(d) \ll 1$, and $\Delta(s) \ll \Delta(d)$ only. The value of $\Delta(s_0^+)$ may be calculated from the condition that the flux of carbon to oceanic depths due to eddy diffusion was equal to influxes and escape fluxes from the reservoir, Eq. (A.4), during the preindustrial era:

$$^{14}F_0^{\pm} = \frac{D}{L}\left[^{14}\mathrm{C}(s_0^{\pm}) - {}^{14}\mathrm{C}(d^{\pm})\right] = \frac{^{14}\mathrm{C}(d^{\pm})H}{^{14}T^{\pm}}. \tag{A.14}$$

Here D is eddy diffusivity and L is the depth above which the ^{14}C concentration gradient is observed. The values D and L remain the same for both organic and inorganic carbon. We have from (A.11) and (A.14):

$$\frac{\Delta(s_0^+) - \Delta(d^+)}{1+\Delta(d^+)}\tau^+ = \frac{\Delta(s_0^-) - \Delta(d^-)}{1+\Delta(d^-)}\tau^- \tag{A.15}$$

and from (A.13) and (A.15):

$$\Delta(s_0^+) = -0.49. \tag{A.16}$$

The present-day influxes of radiocarbon to organic and inorganic reservoirs ($^{14}F^{\pm}$) far exceed their escape fluxes, see (A.1) and are equal to the rate at which the masses of radiocarbon accumulated have kept increasing over the period elapsed since the beginning of surface nuclear tests in 1955 (date of minimum atmospheric radiocarbon; Druffel and Suess, 1983). Such masses are proportional to the areas of the triangles ($d^{\pm}, s^{\pm}, s_1^{\pm}$) cut out by the measured at 1986 (Druffel and Williams, 1990) and the prebomb at 1955 profiles of concentration of radiocarbon, see Fig. 4.4:

$$^{14}\bar{F}^{\pm} = \frac{^{14}C(s^{\pm}) - {}^{14}C(s_1^{\pm})}{2\,\Delta t}L. \tag{A.17}$$

Here $^{14}\bar{F}^{\pm}$ are the radiocarbon fluxes averaged for 1955–1986, $C(s^{\pm})$ and $C(s_1^{\pm})$ designate the oceanic surface radiocarbon concentrations at 1986 and 1955 respectively, $\Delta t = 1986 - 1955 = 31$ years.

The value $\Delta(s_1^+)$ is unknown. This value can be found as follow. The rate of change of DOC mass, $\dot{m}_s^+$, is proportional to the known atmospheric increment of carbon mass, m_a: $\dot{m}_s^+ = k_s^+ m_a$, see (4.4.1), (4.4.2) and (4.12.2) in Sects. 4.4 and 4.12. Integrating this equation over time at constant k_s^+ we find that 43% of total

increment of DOC mass, m_s^+, have been accumulated between 1955 and 1986; (Staffelbach et al., 1991), see Fig. 1.2: Thus using (A.5) and (A.10) we have:

$$[\Delta(s^+) - \Delta(s_1^+)]/[\Delta(s^+) - \Delta(s_0^+)] = 0.43.$$

From the last equation using (A.13) and (A.16) we have:

$$\Delta(s_1^+) = -0.31.$$

The value $\Delta(s_1^-)$ is known from the direct measurements (Druffel and Suess, 1983):

$$\Delta(s_1^-) = -0.06.$$

Recalling that the values of L and Δt are identical for both organic and inorganic carbon, we find from (A.4) and (A.11)–(A.17):

$$\frac{{}^{14}\bar{F}^+/{}^{14}F_0^+}{{}^{14}\bar{F}^-/{}^{14}F_0^-} = \frac{[\Delta(s^+) - \Delta(s_1^+)][1 + \Delta(d^-)]\tau^+}{[\Delta(s^-) - \Delta(s_1^-)][1 + \Delta(d^+)]\tau^-} = 3.1. \tag{A.18}$$

The ratio ${}^{14}F^-/{}^{14}F_0^-$ may be calculated from the total influx of radiocarbon into the ocean: ${}^{14}F = {}^{14}F^- + {}^{14}F^+$. The ratio ${}^{14}F^-/{}^{14}F^+$ from (A.4), (A.13) and (A.14) is equal to ${}^{14}C(d^-)\tau^+/{}^{14}C(d^+)\tau^- \approx 54$. Indeed, the ratio ${}^{14}C(d^-)/{}^{14}C(d^+)$ is equal to the mass ratio of the oceanic dissolved inorganic and organic carbon, which is of the order of 20, see Sect. 4.11. We further obtain from (A.18) that ${}^{14}F^-/{}^{14}F^+$ has decreased by a factor of 3, so that now it approximates to about 18. The ratio ${}^{14}F/{}^{14}F_0$ may be calculated using the well-known expressions (see, for instance, Gorshkov (1987a)):

$${}^{14}F = \frac{b\,{}^{14}C(a) - {}^{14}C(s)}{R_{as}}; \qquad {}^{14}F_0 = \frac{b\,{}^{14}C(a_0) - {}^{14}C(s_0)}{R_{as}}, \tag{A.19}$$

where ${}^{14}C(a)$ and ${}^{14}C(s)$ are concentrations of ${}^{14}CO_2$ in the atmosphere (a) and in the surface ocean (s), R_{as} is the air-sea interface resistance (Gorshkov, 1987a), b is the CO_2 solubility. Recalling that the ${}^{12}C$ concentration is about at equilibrium: $b\,{}^{12}C(a) = {}^{12}C(s)$, dividing the right hand sides of (A.19) by ${}^{12}C(s)$ and ${}^{12}C(s_0)$ respectively, and averaging over time elapsed since land surface nuclear tests ceased (1963–1986) (Druffel and Williams, 1990), we obtain:

$$\frac{{}^{14}\bar{F}}{{}^{14}F_0} = \frac{\bar{\Delta}(a) - \bar{\Delta}(s^-)}{\Delta(a_0) - \Delta(s_0^-)} \approx 7.0, \tag{A.20}$$

$$\frac{{}^{14}\bar{F}^-}{{}^{14}F_0^-} \approx 6.8 \tag{A.21}$$

where $\Delta(a)$ and $\Delta(a_0)$ are taken from publications (see Gorshkov et al., 1990; Druffel and Suess, 1983). As a result we find from (A.17) and (A.19):

$$\frac{{}^{14}\bar{F}^+}{{}^{14}F_0^+} \approx 3.1 \cdot 6.8 \approx 21. \tag{A.22}$$

Taking (A.6) into account we have:

$$\frac{{}^{14}F^+/{}^{14}F_0^+}{{}^{12}F^+/{}^{12}F_0^+} = \frac{{}^{14}R(s^-)}{{}^{14}R(s_0^-)} = \frac{\Delta(s^-) + 1}{\Delta(s_0^-) + 1} = 1.2. \tag{A.23}$$

Finally, we have:

$$\frac{{}^{12}\bar{F}^+}{{}^{12}F_0^+} = \frac{21}{1.2} \approx 18. \tag{A.24}$$

Equations (A.18) and (A.20) are obtained assuming a constant concentration of ${}^{12}C$. In reality the latter has increased in both the ocean surface and the atmosphere by approximately 12–25% (Gorshkov, 1987a; Gorshkov et al., 1990). That effect results in the appearance of factors of the order of 1.12 – 1.25 in $\bar{\Delta}(a)$ and $\bar{\Delta}(s^{\pm})$. However, such adjustments are practically completely compensated for in the final result, (A.22).

The values entering (A.17) are approximately the same for the various regions of the world ocean (Williams and Druffel, 1987; Druffel and Williams, 1990). Only the depths L and H differ, the final result, (A.22) remaining independent of them, however. Therefore, one may assume that the ratio in (A.22) remains typical for the world ocean as a whole. We may retrieve the absolute values of DOC production $P^{+\mathrm{DOC}}$ and $P_0^{+\mathrm{DOC}}$ if we use the relations:

$$P^{+\mathrm{DOC}}/P_0^{+\mathrm{DOC}} = {}^{12}F^+/{}^{12}F_0^+; \quad P_0^{+\mathrm{DOC}} = M_0^{\mathrm{DOC}}/{}^{12}T^+,$$

where M_0^{DOC} is the total preindustrial mass of DOC. The modern estimation of DOC mass is, $M^{\mathrm{DOC}} \approx 2000$ Gt C (Sugimura and Suzuki, 1988; Ogawa and Ogura, 1992; Martin and Fitzwater, 1992). The total DOC mass increment is about 15–20% of M^{DOC} that is less than the uncertainties of the value of M^{DOC}. So we can put $M_0^{\mathrm{DOC}} \approx M^{\mathrm{DOC}}$. The average residence time for ^{12}C in its dissolved organic form is ${}^{12}T^+ = 8400$ years, see (A.13). Thus we obtain:

$$P_0^{+\mathrm{DOC}} = P_0^{-\mathrm{DOC}} = 0.24 \text{ Gt C/year}, \qquad P^{+\mathrm{DOC}} = 4.2 \text{ Gt C/year} \tag{A.25}$$

For the rate of DOC accumulation, $\dot{m}_s^+$, we have:

$$\bar{\dot{m}}_s^+ = \bar{P}^{+\mathrm{DOC}} - \bar{P}^{-\mathrm{DOC}} = 4.0 \text{ Gt C/year}, \tag{A.26}$$

where the variable $\bar{P}^{+\mathrm{DOC}}$ corresponds to the average production of the dissolved organic carbon (DOC) over the period 1955–1986, and $P^{-\mathrm{DOC}} = P_0^{-\mathrm{DOC}}$. The uncertainties of the result in (A.24) and (A.25) are less than 20%. They are determined mainly by the uncertainty in the accepted mean value M_0^{DOC}.

The total mass of particulate organic carbon (POC) is of the order of several per cent of the total DOC mass (Mopper and Degens, 1979; Druffel and Williams, 1990). The possible rate of POC mass change due to change of POC production, sinking or destruction is, in any case, negligibly small as compared with the obtained DOC mass change (A.25).

Appendix B
Details of Calculations in Sect. 4.12

The carbon rates of change $\dot{m}_s^+$ and $\dot{m}_s^-$ and the coefficients k_s^+ and k_s^-, Eq. (4.12.2), may be directly retrieved from the observable changes of distributions of ^{13}C and ^{14}C in the DOC and DIC (see Appendix A) within the world ocean without using the unreliable value of global average air-to-sea exchange coefficient, see (Broecker et al., 1986; Gorshkov, 1987a, 1993b; Etcheto et al., 1991).

The value of k_s^+ may be retrieved from (4.12.2) and (A.26) taking the average for the years of 1955–1986 at $\dot{m}_s^+ = 4.0$ Gt C/year, $m_a \approx 106$ Gt C (Trivett, 1989; Gorshkov et al., 1990):

$$k_s^+ = \frac{\dot{m}_s^+}{m_a} = 0.038 \text{ year}^{-1}. \tag{B.1}$$

To obtain the k_s^- coefficient we may use the data on the distribution of ^{13}C in the world ocean (Quay et al., 1992). Equation (4.12.1) may be used for two carbon isotopes ^{12}C and ^{13}C. The rate of change for $^{13}\dot{m}_i$ may be written in the form:

$$^{13}\dot{m}_i \equiv \frac{d}{dt}(^{13}M) = \frac{d}{dt}(M_i\,^{13}R_i) = \dot{m}_i\,^{13}R_i + M_i\,^{13}\dot{R}_i, \tag{B.2}$$

$$M_i \equiv {}^{12}M_i,\ \dot{m}_i \equiv \frac{d}{dt}M_i,\ {}^{13}R_i \equiv \frac{^{13}M_i}{^{12}M_i}. \tag{B.3}$$

The land and oceanic biomasses have approximately equal ratios ^{13}R: $^{13}R_b \approx {}^{13}R_s^+$ (Degens at al., 1968, 1984; Gorshkov, 1987a). The total organic mass of the land + oceanic biota is $M_B \equiv M_b + M_s^+$ and their increment is $m_B \equiv m_b + m_s^+$. Equation (4.12.1) for ^{12}C and ^{13}C have the form:

$$\dot{m}_a + \dot{m}_f + \dot{m}_s^- + \dot{m}_B = 0, \tag{B.4}$$

$$\begin{aligned} &\dot{m}_a\,^{13}R_a + \dot{m}_f\,^{13}R_f + \dot{m}_s^-\,^{13}R_s^- + \dot{m}_B\,^{13}R_B + \\ &M_a\,^{13}\dot{R}_a + M_s^-\,^{13}\dot{R}_s^- + M_B\,^{13}\dot{R}_B = 0;\ \ (^{13}\dot{R}_f = 0). \end{aligned} \tag{B.5}$$

Using the notation (see (A.10)):

$$\delta_i \equiv \delta\,^{13}C_i \equiv (^{13}R_i/^{13}R^S) - 1 \tag{B.6}$$

we obtain from (B.2) and (B.3):

$$\begin{array}{lllllll} \dot{m}_s^- = & -\frac{\delta_a-\delta_B}{\delta_s^- - \delta_B}\dot{m}_a & -\frac{\delta_f-\delta_B}{\delta_s^- - \delta_B}\dot{m}_f & -\frac{\dot{\delta}_a M_a}{\delta_s^- - \delta_B} & -\frac{\dot{\delta}_s^- M_s^-}{\delta_s^- - \delta_B} & -\frac{\dot{\delta}_B M_B}{\delta_s^- - \delta_B}, \\ 2.1 = & -1.8 & -0.38 & -0.59 & +3.7 & -0.03 \end{array} \tag{B.7}$$

$$\begin{array}{lll} \dot{m}_B = & -\dot{m}_a & -\dot{m}_f & -\dot{m}_s^-. \\ 0.1 = & -2.9 & +5.1 & -2.1 \end{array} \tag{B.8}$$

The figures below respective terms give their observed values in Gt C /year for the period 1970–1990. The leading term, $\delta_s^- M_s^-$, on the right hand side of (B.7) within the world ocean is obtained by Quay et al. (1992). Note that the rate of change of the total biomass $\dot{m}_B = \dot{m}_s^+ + \dot{m}_b$ is approximately equal to zero, i.e. $\dot{m}_s^+ \approx -\dot{m}_b$. Therefore the observed changes of global oxygen stores and fluxes (Keeling and Shertz, 1992) cannot provide evidence of rates of biomass change. The value of k_s^- may be retrieved from (B.7) and (4.12.2) taking the average for years 1970–1990 at $\dot{m}_s^- = 2.1$ Gt C/year, $m_a \approx 130$ Gt C (Trivett, 1989):

$$k_s^- = 0.016 \text{ year}^{-1}. \tag{B.9}$$

Finally, we obtain for k_s (see (B.1)):

$$k_s = k_s^+ + k_s^- = 0.054 \text{ year}^{-1}, \qquad \frac{k_s^+}{k_s^-} = 2.4. \tag{B.10}$$

The solution of (4.12.1) and (4.12.2) at constant k_s is as follows:

$$M_a(t) - M_a(t_0) = \int_{t_0}^{t} G(t-t')\dot{m}_A(t')at \tag{B.11}$$

$$G(t-t') = e^{k_s(t-t')}, \qquad \dot{m}_A(t) \equiv \dot{m}_f(t) + \dot{m}_b(t).$$

The solution (B.11) has analytical form in the case of logistic behavior of the total anthropogenic perturbation $\dot{m}_A(t)$ (Gorshkov, 1982c). If $\dot{m}_A(t)$ is constant in the future ($\dot{m}_A(t) = \dot{m}_A(t_0)$, $t_0 = 1990$ years) the solution (B.11) has a simple form:

$$M_a(t) - M_a(t_0) = \frac{\dot{m}_A(t_0)}{k_s}\left[1 - e^{-k_s(t-t_0)}\right]. \tag{B.12}$$

Taking into account that a carbon mass of 2.1 Gt C corresponds to a carbon concentration 1 ppmv in the atmosphere (Watts, 1982) and using the numerical values, see Figs. 4.5–10, we obtain that asymptotic atmospheric concentration will not be larger than 460 ppmv:

$$[CO_2]_a = \{350 + 110[1 - e^{-0.054(t_{A.D.}-1990)}]\} \text{ ppmv}. \tag{B.13}$$

However the real behavior of $\dot{m}_A(t)$ is not known and the coefficient k_s may not be constant if the perturbation $\dot{m}_A(t)$ should increase in the future, see Sect. 4.12.

Appendix C
Details of Calculations of the Results in Fig. 6.2

In Fig. 6.2, points 1–12 denote the average expenditures of energy on cultivated fields in 1964–1965 in different countries (Meadows et al., 1974). Manual labor corresponding to 10 W/person is added to points 9–12; the data of Starr (1971) and Hubbert (1971) correspond to the lower limit of the error cited. The crosses 1–6 were computed from data on total energy consumption (including consumption of the products of the biosphere) and grain production in the entire country. The deviation of the points from the curve is related to the difference between the value of the productivity and the world-average value. The points showing high productivity to the left of the curve are balanced by point 7, corresponding to half of the population on Earth.

Remaining data:

Point 13 – traditional agriculture (Russian, 1897) using working livestock. Computations from the data: average productivity, 0.6 t/(ha year) of grain (World Food Problem, 1967; Meadows et al., 1974); 1 horse per 4 ha of plowed field (Yuzhakov, 1904), average mass of a horse, 400 kg; grain equivalent: of consumption by a horse, five times its mass per year or 2000 kg/year or 1000 W (Brody, 1945) developed in the meadows and pasture-land; average consumption power by horse in the fields, 250 W/ha or 210 W/person (for production of 500 kg/year of grain); average working power of a horse, 125 W (one-eighth of the consumption (Brody, 1945)), average working power of a horse in the fields, 31 W/ha or 26 W/person (for 500 kg/year of grain); average power of manual labor in the fields 5 W/person (plowman with an average power of 15 W, feeding three people, including himself), i.e. $S = 0.83$ ha/person, $w_{agr} = 31$ W/person, $w_{tot} = 540$ W/person (134 W/person for food, 200 W (about 1.5 times the food power) for fire, 210 W for the horse).

Point 14 – slash-and-burn agriculture using manual labor with an average power $w_{agr} = 10$ W/person with productivity of 0.6 t/(ha year) during the cultivation periods and a regenerating period equal to ten of the cultivation periods: $S = 8.3$ ha/person, $w_{tot} = 300$ W/person (134 W for man food and 170 W for the fire used).

Point 14a – present tropical slash-and-burn agriculture practiced by the people of Tsembaga (Rappaport, 1971); the productivity during the periods of cultivation, 6.3 t/(ha year) of grain; regeneration time, 25 years; $S = 2$ ha/person; ratio of the

energy in the harvest to the energy expended equals 16; $w_{agr} = 15$ W/person (per 500 kg of grain), $w_{tot} = w_{tot}^{(14)} = 300$ W/person.

Point 15 – primitive foraging without the use of fire; $S = 500$ ha/person; $w_{agr} = 6.6$ W/person; $w_{tot} = 134$ W/person; the quantities are computed on the basis of $S = 3 \times 10^7 \cdot l^2$ (territory intermediate between that of an herbivorous mammal, $10^7 \cdot l^2$, and that of a predator, $10^8 \cdot l^2$ (Calder, 1974; King, 1974), where l is the linear size (for man $l = 0.4$ m) and the motive power $w_{agr} = Fu$ for moving about the territory with an average speed $u = S/(l_{eff}\tau) \sim 0.17$ m/s = 14 km/day; it is assumed that in moving about a man forages over a strip of width $l_{eff} = 1$ m, where $\tau = 1$ year, the time for producing the food required for one year, $F = \gamma_a$ mg is the force, proportional to the weight, $\gamma_a = 6 \times 10^{-2}$ (Brody, 1945), see Fig. 5.6.

Point 16 – primitive fishing; $S = 10^4$ ha/person, computed from the average catch of 1–2 kg/(ha year) of live mass; the energy expenditure of the fisherman and the forager are taken as equal.

Point 16a – present-day marine fishing; computed from data on present-day catch of 7×10^7 t per year of live mass from an ocean area of 3.6×10^{10} ha; over-all power of world fishing fleet estimated at 1.5 times the calorific value of the fish caught (Meadows et al., 1972, 1974; Mesarovic and Pestel, 1974; Odum, 1983).

Point 17a – traditional animal husbandry using pastures, providing a consumption of 280 kg/year person of animal production calorie-equivalent to grain with a coefficient of transformation of vegetative energy into the animal production equal to 14 (twice as great as for the transformation of grain into meat (Meadows et al., 1974)), with average primary productivity of pasture land, 3 t (dry mass)/(ha year) or 1.4 t C/(ha year) or 1.8 W (ha year) (Brody, 1945; Whittaker and Likens, 1975; Odum, 1983) and with the present-day world-average grazing standards (20 % of the total primary production of pastures is consumed); $w_{agr} = 8$ W/person, determined mainly by expenditures of energy on maintaining pastures, taken as equal to one-quarter (present ratio of the expenditures of energy on pastures and on plowed fields (Burwell, 1978; Odum, 1983)) of the average expenditures of energy on pastures in niche 13; $S = 8.4$ ha/person; $w_{tot} = 240$ W/person (134 W as food for man, 80 W as cooking fire (60 % of the production from livestock (milk) is eaten in its raw form), 40 W as food for dogs) (Whittaker and Likens, 1975; Harlan, 1976; Janick et al., 1976; Schrimshaw and Young, 1976; Wortman, 1976);

Point 17b – primitive animal husbandry using pastures with 0.02 % of the production of pastures consumed at a rate 1000 times less than in 17a (two times greater than the consumption by corresponding wild animals)(McNeill and Lawton, 1970; Calder, 1974; King, 1974); $S = 10^4$ ha/person. As in 15, energy expenditures are determined by the movement of the herder over the pasture with $l_{eff} = 30$ m (average distance separating the sheep and the sheep herder); the herder eats eight times his weight per year, i.e., about 10 sheep, with a reproduction time for the sheep of the order of three years. Correspondingly, the herder must own a herd of 30 head; $w_{agr} = S/(l_{eff}\tau_1) = 6$ W/person ($\tau_1 \sim 1$ year, the regenerating time of vegetation); $w_{tot} = w_{tot}^{(17a)} = 250$ W/person.

Niches 17a,b corresponding to animal husbandry in pastures are most energy self-sufficient.

Point 17c – present-day animal husbandry in stalls using the production of pastures with a coefficient for transformation of energy from grain into energy of animal production equal to $\alpha_2 = 1/7$ (Meadows et al., 1974) and consumption of $7 \cdot 280$ kg/(year·person) = 2000 kg/(year·person) of grain is four times greater than that given in niche 6;

$S = 4S^{(6)} = 1.6$ ha/person; $w_{agr} = 4w_{agr}^{(6)} = 400$ W/person;

$w_{tot} = 4w_{tot}^{(6)} = 24$ kW/person.

The niches 17c and 16a are territory and energy consuming. They can be used only when production exchange with other niches is available.

Point 18 – hunting on foot with one dog per person; $w_{agr} = 12$ W/person; $S = 2 \times 10^4$ ha/person; $w_{tot} = 240$ W/person $= w_{tot}^{(16)}$. The territory is estimated by postulating existence supported by a single species of game with a normal average biomass density of 210 g/ha of live weight ($\sim$ 52 g/ha of dry mass (Calder, 1974; King, 1974; Andrijanov, 1978). (In Andrijanov, 1978 the territory of a hunter in Siberia is estimated as $(2\text{–}3) \times 10^4$ ha/person), a regeneration time τ of the order of 1 year and harvesting of 25 % of the production of game. The power developed by the hunter corresponds to movement over the territory with an average speed of $u = 0.2$ m/s = 20 km/day (see niche 15), $l_{eff} = 30$ m, corresponding to an armed hunter making a kill at a distance of 15 m. The power involved in stalking and making a kill is taken as equal to one-quarter of the motive power involved in stalking. The motive power associated with a dog equals one-quarter of the motive power of a human.

Point 18a – present-day hunting by Eskimos (Kemp, 1971) (Canada, Baffin Island). The territory is estimated from the attached map as $S = 10^5$ ha/person (2.3×10^6 ha per 26 persons); $w_{agr} = 40$ W/person (30 W/person for gasoline engines, 10 W as the motive power of a man and a dog), $w_{tot} = 400$ W/person (170 W/person for gasoline, 50 W/person for kerosine or seal oil for heating a dwelling, 134 W/person for food for people, 40 W/person for dog food), the efficiency of the engines is assumed equal to 20 % (Summers, 1971).

Point 19 – hunting on horseback for large animals (bison, regenerating time $\tau \sim 3$ years) with one horse per person. The motive power of a horse $w_{agr} = 100$ W $= \gamma_h mgu$; $\gamma_h = 0.04$ (Schneider, 1976), $u = 0.63$ m/s = 54 km/day $= S/(l_{eff}\tau)$, $l_{eff} = 30$ m, $\tau = 3$ years, $S = u\tau l_{eff} = 3 \times 10^5$ ha/person, $w_{tot} = 1300$ W/person (1000 W for the horse, 134 W for the man, 150 W for fire).

Point 20 – motorized hunting; $l_{eff} = 50$ m, $S = 10^6$ ha/person, $u = 6.4$ m/s = 550 km/day, $\tau = 1$ year, $w_{agr} = \gamma_M mgu = 800$ W/person = 1 hp/person, $\gamma_M = 0.04$, m = 300 kg (mass of the machine including the person), $w_{tot} \sim 7000$ W/person; the efficiency of the engine is 20 % (Summers, 1971), the power for manufacturing the engines (fraction of the total energy used by our civilization) is taken as equal to the power of the engine (Cook, 1971).

In niches 19 and 20, existence supported by hunting is possible with game having a biomass density less than the average normal value (niche 18) by a factor of 15 and 50, respectively.

Estimates of the errors in the values of w and S for the average productivity of land (0.5 W/m^2) are shown on the graph.

Appendix D
List of Frequently Used Symbols

Symbol	Definition and Units	First Use
	Chapter 2	
T_S	absolute temperature of the Sun's surface, K	Sect. 2.2
T_o	absolute temperature of the Earth's surface, K	Sect. 2.2
η	maximum radiation efficiency, dimensionless	Sect. 2.2
I_S	solar constant, W/m^2	Eq. (2.2.1)
I	average relative flux of solar radiation per unit area of the Earth's surface, W/m^2	Eq. (2.2.1)
I_e	average absorbed flux of solar radiation per unit area of the Earth's surface, W/m^2	Eq. (2.2.2)
A	Earth's planetary albedo, dimensionless	Eq. (2.2.2)
I_o	average flux of solar radiation absorbed by the surface of the Earth, W/m^2	Eq. (2.2.3)
k_B	Boltzmann's constant, JK^{-1}molecule^{-1}	Sect. 2.3
T	absolute temperature, K	Sect. 2.3
t °C	temperature, degrees Centigrade	Sect. 2.3
N_A	Avogadro's number, molecule/mole	Sect. 2.3
n_E	number of moles of matter	Eq. (2.3.1)
E	energy of mole of matter, J/mole	Eq. (2.3.1)
R	gas constant, JK^{-1}mole^{-1}	Eq. (2.3.1)
N	number of molecules or of particles	Sect. 2.3,
$z(t)$	measurable, time-dependent variable	Eq. (2.6.1)
$\dot{z}(t)$	time derivative of $z(t)$	Eq. (2.6.1)
$k(t)$	relative temporal rate	Eq. (2.6.1)
l	length, m	Eq. (2.6.2)
g	acceleration of free fall, m/s^2	Eq. (2.6.2)
u	speed, m/s	Eq. (2.6.2)
Fr	Froude number, dimensionless	Eq. (2.6.3)
z	measurable variable of a given dimension	Eq. (2.6.4)
β	dimensionless coefficient of proportionality between the relative changes of two variables of differing dimension	Eq. (2.6.4)
l_e	arbitrary unit of length	Eq. (2.6.7)
x	logarithm of length l measured in units l_e	Eq. (2.6.7)
z_e	arbitrary unit of measurable variable z	Eq. (2.6.7)
y	logarithm of z measured in units z_e	Eq. (2.6.7)
z'	slope of scale invariance x-dependence of y	Eq. (2.6.8)
q_e	flux of effective thermal radiation emitted by planet into outer space, W/m^2	Eq. (2.7.1)
c	thermal heat capacity, JK^{-1}m^{-3}	Eq. (2.7.2)
q_{e0}; I_{e0}; A_0	equilibrium values of q_e; T_e; A	Eq. (2.7.2)
σ	Stephan-Boltzmann constant, Wm^{-2}K^{-4}	Eq. (2.7.3)
q_R	thermal radiation flux of the planet at zero albedo, W/m^2	Table 2.7
T_R	temperature of planet surface at zero albedo and greenhouse effect, K	Table 2.7
T_e	effective temperature of planetary thermal emission, K	Table 2.7
q	planetary surface thermal emission, W/m^2	Eq. (2.7.4)
q_0	equilibrium value of q, W/m^2	Table 2.7
α; α_0	normalized greenhouse effect; its equilibrium value	Eq. (2.7.4)
z	relative change of temperature	Eq. (2.7.9)

Symbol	Definition and Units	First Use
k_0	coefficient of stability , year^{-1}	Eq. (2.7.9)
c_0	equilibrium heat capacity , JK^{-1}m^{-3}	Eq. (2.7.9)
λ_0	sensitivity of climate , Wm^{-2}K^{-1}	Eq. (2.7.9)
$A_0'; \alpha_0'$	derivatives over temperature of $A_0; \alpha_0$	Eq. (2.7.10)
N_e	flux of Earth's long-wave photons into space, photons m^{-2}s^{-1}	Eq. (2.8.1)
N_s	flux of short-wave solar photons absorbed by the Earth, photons m^{-2}s^{-1}	Eq. (2.8.2)
η_e	efficiency for solar energy, dimensionless	Eq. (2.8.3)
n_e	average number of long-wave terrestrial photons into which a single short-wave solar photon decays	Eq. (2.8.4)
$q_{\min}$	minimal possible flux of Earth's thermal radiation, W/m^2	Eq. (2.8.5)
	Chapter 3	
v	probability of random point mutation per nucleotide site, per division, (bp)$^{-1}$d^{-1}	Eq. (3.4.1)
M	genome size (number of nucleotide pairs in genome), bp	Sect. 3.4
μ	decay rate (number of random mutations per genome per generation), dimensionless	Eq. (3.4.2)
$k_g; k_{wg}; k_{mg}$	number of cell divisions in the germ line; for women; for men, d	Eq. (3.4.2)
n	number of mutations or nucleotide substitutions	Eq. (3.4.3)
N_0	number of normal individuals in the population containing no deleterious substitutions in their genomes	Eq. (3.5.1)
N_n	number of decay individuals containing n decay deleterious substitutions in their genomes	Eq. (3.5.1)
$\dot{N}_n$	time derivative of N_n	Eq. (3.5.1)
$b_n; d_n$	birth rate (fertility); death rate of individual containing n deleterious substitutions in their genome, year^{-1}	Eq. (3.5.1)

Symbol	Definition and Units	First Use
$B_n = b_n e^{-\mu}$	birth rate share of offspring containing no changes in their genomes as compared to the parent genome, year^{-1}	Eq. (3.5.1)
B	B_n in the case when neither birth nor death rate of decay individuals is regulated, year^{-1}	Eq. (3.5.1)
n_L	lethal threshold of the number of deleterious substitutions	Sect. 3.5
δ_{nn_L}	Kronecker symbol	Eq. (3.5.5)
T_s	average lifespan of the species, year^{-1}	Sect. 3.5
β_n	relative birth rate, dimensionless	Eq. (3.5.6)
δ_n	relative death rate, dimensionless	Eq. (3.5.6)
γ_n	noncompetitiveness, dimensionless	Eq. (3.5.10)
W	absolute fitness, year^{-1}	Sect. 3.5
w	relative fitness, dimensionless	Sect. 3.5
s	coefficient of selection, dimensionless	Sect. 3.5
$w_n; s_n$	fitness; coefficient of selection of decay individuals containing n deleterious substitutions	Eq. (3.5.11)
n_c	maximum number of decay (deleterious) substitutions evading detection during competitive interaction of individuals (sensitivity threshold of competitive interaction or threshold of truncating selection in natural conditions). All individuals containing $n < n_c$ have the normal genotype	Sect. 3.6
$r_c \equiv n_c/M$	average permitted density of decay substitutions in the normal genome, dimensionless	Sect. 3.6
$l_c \equiv r_c^{-1}$	average relative length of the normal genome free of decay substitutions, dimensionless	Sect. 3.6
τ_g	time lapse between the two successive cell divisions in germ line, s	Sect. 3.7
n_0	number of neutral sites in which neutral substitutions may arise	Sect. 3.7

Symbol	Definition and Units	First Use
N_u	population number in which a neutral mutation occurs at a probability of unity in each single generation	Sect. 3.7
ν_{12}	probability of transition from state 1 to state 2	Sect. 3.7
$n_{\min} > n_c$	minimal number of decay substitutions in the perturbed external conditions	Sect. 3.9
μ_{gen}	decay rate of a single gene (number of mutations per gene per generation)	Sect. 3.11
μ_s	somatic decay rate (number of mutations per genome in somatic line)	Sect. 3.12
k_s	number of divisions in somatic line	Eq. (3.12.1)
H	heterozygosity of diploid genome (including X and Y chromosomes)	Sect. 3.13
μ_{2s}	diploid somatic decay rate	Eq. (3.13.1)
μ_{ns}	n-ploid somatic decay rate	Eq. (3.13.2)
M_n	total length of n-ploid genome (total length of all chromosomes), bp	Sect. 3.13
H_n	heterozygosity of n-ploid genome, dimensionless	Eq. (3.13.3)
H_0	heterozygosity corresponding to X and Y chromosome (X and Y chromosomes to total genome length ratio)	Eq. (3.13.5)
H_c	maximum heterozygosity of normal genotype: individuals of heterozygosity below H_c have equal competitiveness	Eq. (3.13.5)
H_L	lethal threshold of heterozygosity	Eq. (3.13.6)
$\mu^- \equiv \mu$	decay rate of genome, dimensionless	Sect. 3.15
μ^+	generative rate of genome (number of progressive mutations per genome per generation), dimensionless	Eq. (3.15.1)
κ_e	ratio of decay to progressive mutations in eukaryotes	Eq. (3.5.1)

Symbol	Definition and Units	First Use
κ_p	ratio of decay to progressive mutations in prokaryotes	Eq. (3.15.2)
$v^- \equiv v$	probability of a decay mutation per nucleotide site per division, $(\text{bp})^{-1}\text{d}^{-1}$	Eq. (3.15.1)
v^+	probability of a progressive mutation per nucleotide site per division, $(\text{bp})^{-1}\text{d}^{-1}$	Eq. (3.15.1)
T_e	age of life (complete time of biological evolution), years	Sect. 3.17
	Chapter 4	
T	time interval of evolutionary change, that is the order of mean lifespan of species, T_s, year	Sect. 4.2
τ	time of noticeable change of the store of nutrients in the environment of order of residence time, year	Sect. 4.2
$M^\pm$	mass of organic (+) and inorganic (−) nutrients per unit surface area, kg m^{-2}	Sect. 4.2
$\dot{M}^\pm$	time derivative of $M^\pm$, kg $\text{m}^{-2}\text{year}^{-1}$	Eq. (4.3.1)
$P^\pm$	productivity (+) and destructivity (−) of organic matter, kg m^{-2} year^{-1}	Eq. (4.3.1)
$F^\pm$	net physical flux of organic matter evacuated from (+) and inorganic matter imported into (−) one reservoir, kg m^{-2} year^{-1}	Eq. (4.3.1)
$F^\pm_{\text{in}}, F^\pm_{\text{out}}$	overall input, output fluxes, kg m^{-2} year^{-1}	Sect. 4.3
κ	breach of biological cycles (relative difference between production and destruction of organic matter), dimensionless	Eq. (4.3.2)
$\nu^\pm; \nu^\pm_{\text{in}}$	net; gross openness of a reservoir, dimensionless	Eq. (4.3.3)
$T^\pm$	time of complete restructuring of the environment, years	Eq. (4.3.4)
$\tau^\pm$	residence time of organic (+) and inorganic (−) matter, years	Eq. (4.3.4)
κ_0	equilibrium breach κ	Eq. (4.3.5)

Symbol	Definition and Units	First Use
$\kappa_l; \kappa_s$	breach on land (l); in ocean (s)	Eq. (4.3.7)
$\alpha_l; \alpha_s$	relative land and ocean production, dimensionless	Eq. (4.3.7)
ν_l	openness on land	Sect. 4.3
X	chemical element in either organic or inorganic nutrient	Sect. 4.4
$P_X^{\pm}$	productivity (+) and destructivity (−) of nutrient X, kg X m^{-2} $year^{-1}$	Eq. (4.4.1)
$M_X^{\pm}$	mass of nutrient X in organic (+) and inorganic (−) matter per unit surface area, kg X m^{-2}	Eq. (4.4.1)
$m^{\pm}$	mass increment, kg X m^{-2}	Eq. (4.4.1)
β_X	slope of scaling relation, dimensionless	Eq. (4.4.1)
k	stability coefficient, $year^{-1}$	Eq. (4.4.2)
$[X_{in}]$; $[X_{out}]$	concentration of nutrient X inside and outside local ecosystem, kg X m^{-3}	Sect. 4.6
$\Delta[X]$	difference in concentration inside and outside the local ecosystem, kg X m^{-3}	Sect. 4.6
ε	relative change in the concentration X	Sect. 4.6
ε_{min}	sensitivity limit	Sect. 4.6
$\Delta_y[X]$; $\Delta_z[X]$	concentration difference of nutrient X in horizontal (y) and vertical (z) directions, kg X m^{-3}	Sect. 4.6
D	diffusivity, m^2/year	Eq. (4.6.1)
H_e	vertical size of local ecosystem, m	Eq. (4.6.1)
R_e	external resistance to diffusion transport, year/m	Eq. (4.6.1)
R_i	internal resistance to synthesis of organic matter, year/m	Eq. (4.6.3)
R_{iX_k}	internal resistance to synthesis organic nutrient X_k, year/m	Eq. (4.7.2)
$[X_{min}]$	minimum concentration below which life becomes impossible, kg X m^{-3}	Sect. 4.7

Symbol	Definition and Units	First Use
$[X_{max}]$	maximum concentration related to the maximum productivity at a prescribed incoming flux of external energy, kg X m^{-3}	Sect. 4.7
$M_\alpha^+; P_\alpha^{\pm}$; $F^{\pm}_{\alpha\,in,out}$	biomass (population number) ; birth (+) and death (−) rates, $year^{-1}$; immigration (in) and emigration (out), $year^{-1}$, in unit surface area of individuals of unit body mass of the α species	Eq. (4.8.2)
$\nu^+_{\alpha\,in} \equiv F^+_{\alpha\,in}/P^+_\alpha$	species α openness of the local ecosystem, dimensionless	Eq. (4.8.2)
$[\alpha]$	concentration of individuals of the α species	Eq. (4.8.3)
D_α	horizontal diffusivity of individuals of the α species, m^2/year	Eq. (4.8.3)
L	horizontal size of community (local ecosystem), m	Eq. (4.8.3)
H_α	vertical dimension occupied by the α species in a community, m	Eq. (4.8.3)
$[\Sigma CO_2]$	total surface concentration of dissolved inorganic carbon, mole C/m^3	Eq. (4.9.1)
$[CO_2]$	surface concentration of dissolved CO_2 molecules, mole C/m^3	Eq. (4.9.1)
$[HCO_3^-]$; $[CO_3^{2-}]$	surface concentration of bicarbonate and carbonate ions, mole C/m^3	Eq. (4.9.1)
$\Delta[CO_2]$; $\Delta[\Sigma CO_2]$	$[CO_2]$; $[\Sigma CO_2]$ increments, mole C/m^3	Eq. (4.9.2)
ζ	buffer (Revelle) factor, dimensionless	Eq. (4.9.2)
$A_C^+; A^+$	carbonate; total (titrate) alkalinity, mole/m^3	Eq. (4.9.3)
$[CO_2]_a$	concentration of atmospheric CO_2, mole C/m^3	Eq. 4.9.7)
ξ	equilibrium atmospheric to total dissolved inorganic carbon concentration ratio, dimensionless	Eq. (4.9.7)
$m_a; m_s^{\pm}$	increment of carbon mass in atmosphere (a) and ocean (s) in organic (+) and inorganic (−) forms, Gt C	Eq. (4.9.8)

Symbol	Definition and Units	First Use
$V_a; V_s$	volume of the atmosphere (a) and of the world ocean (s), m^3	Eq. (4.9.8.)
Z	ocean depth, m	Sect. 4.10
$F_X^{\pm}(Z)$	net flux of nutrient X in organic (+) and inorganic (−) form at depth Z, mole C m^{-2} $year^{-1}$	Eq. (4.10.1)
$D(Z)$	eddy diffusivity at depth Z, m^2/year	Eq. (4.10.2)
$b(Z)$	difference between the densities of destruction and production of organic matter per unit volume at depth Z, mole C m^{-3} $year^{-1}$	Eq. (4.10.3)
$P_n^{\pm}, P_{nX}^{\pm}$	new productivity (+) and destructivity (−) of organic matter, of nutrient X, mole C m^{-2} $year^{-1}$	Eqs. (4.10.4) and (4.10.8)
$P_g^{\pm}, P_{gX}^{\pm}$	gross (total) and net primary productivity (+) and destructivity (−) of organic matter of nutrient X, and (4.10.10) mole C m^{-2} $year^{-1}$	Eqs. (4.10.4)
H	depth at which concentration gradients become zero, m	Eq. (4.10.4)
$f = \frac{P_n^+}{P_g^+}$	new to total productivity ratio, dimensionless	Eq. (4.10.4)
$L^{\pm}$	average depth at which new production is synthesized (+) and destroyed (−), m	Eq. (4.10.5)
$\delta(Z), \vartheta(Z)$	Dirac delta-function, step function	Eq. (4.10.6)
$[X]_s; [X]_d$	surface and deep concentration of inorganic X, mole X/m^3	Eq. (4.10.8)
L_s	depth of the well-mixed surface layer, m	Eq. (4.10.9)
L_e	depth of layer in which the gradient of nutrient concentration is observed, m	Eq. (4.10.9)
D_e	average diffusivity in the layer L_e, m^2/year	Eq. (4.10.9)
R_e	external resistance, year/m	Eq. (4.10.9)
R_{gX}, R_{nX}	internal resistance corresponding to gross, new production of organic nutrient X, year/m	Eq. (4.10.10)
$b \equiv [CO_2]_s/[CO_2]_a$	solubility of CO_2, dimensionless	Eq. (4.10.12)

Symbol	Definition and Units	First Use
$[CO_2]_{max}$, $[CO_2]_{min}$	maximum ($P_n^+ = 0$), minimum ($P_n^+ = P_g^+$) atmospheric CO_2 concentration, mole C/m^3	Eqs. (4.10.13) and (4.10.14)
$P^{\pm DOC}$	productivity (+) and destructivity (−) of the dissolved organic carbon, Gt C/year	Eq. (4.11.1)
$P_0^{\pm DOC}$	preindustrial value of $P^{\pm DOC}$, Gt C/year	Eq. (4.11.2)
$\dot{m}_a; \dot{m}_s; \dot{m}_f; \dot{m}_b$	rate of change of carbon mass in the atmosphere (a); ocean (s); fossil fuel (f); land biota (b), Gt C/year	Eq. (4.12.1)
k_s	carbon stability (relaxation) coefficient for the world ocean, $year^{-1}$	Eq. (4.12.2)
$k_s^{\pm}$	physico-chemical (−) and biological (+) carbon stability coefficient for the world ocean, $year^{-1}$	Sect. 4.12
$P_s^{\pm}; P_{s0}^{\pm}$	recent and preindustrial ocean gross primary productivity (+) and destructivity (−), kg Cm^{-2} $year^{-1}$	Eq. (4.12.3)
$\Delta P_s^{\pm} \equiv P_s^{\pm} - P_{s0}^{\pm}$	increment of $P_s^{\pm}$, kg C m^{-2} $year^{-1}$	Eq. (4.12.3)
β_s^+	slope of the scaling relation for the global carbon change, dimensionless	Eq. (4.12.4)
τ_s^+	turnover time of atmospheric carbon in the oceanic biota, year	Eq. (4.12.4)
M_{a0}	preindustrial (equilibrium) atmospheric carbon mass, Gt C	Eq. (4.12.4)
$k_a; k_s; k_f; k_b$	carbon stability coefficient of the atmosphere (a); ocean (s); fossil fuel (f); land biota (b), $year^{-1}$	Eq. (4.12.6)
	Chapter 5	
$K_C; K$	energy content per unit mass of organic carbon J (kg C)$^{-1}$ and per unit living body mass, J kg^{-1}	Eqs. (5.1.1) and (5.1.2)
ω, T^+	average velocity of all the body's molecules after instant combustion of all their body organics, their absolute temperature	Eqs. (5.1.2) and (5.1.3)
R	gas constant, $JK^{-1}mole^{-1}$	Eq. (5.1.3)
T_0	average absolute temperature of the Earth's surface, K	Eq. (5.1.3)

Symbol	Definition and Units	First Use
η	maximum efficiency of internal energy expenditure for living individuals, dimensionless	Eq. (5.1.3)
q; $Q \equiv q/K$; $Q_C \equiv q/K_C$	metabolic rate in power units, W; in living mass units, kg year^{-1}; and in carbon units, kg C year^{-1}	Sect. 5.1
$q(T)$	temperature dependence of metabolic rate, W	Sect. 5.1
Q_{10}	ratio $q(T + 10°C)/q(T)$, dimensionless	Sect. 5.1
q_0	basal metabolic rate (power), W	Eq. (5.1.4)
A; $\bar{A}$	total activity; mean total existence activity, dimensionless	Eq. (5.1.4)
m; mg	body mass, kg; body weight, N	Eq. (5.2.1)
ρ	water (living body) density, kg/m^3	Sect. 5.2
l; s	effective individual size, m; Earth's surface projection area, m^2	Eq. (5.2.1)
g	acceleration of free fall, m/s^2	Eq. (5.2.2)
j; λ; $\hat{\lambda}$	metabolic rate (power) per unit body projection area, W/m^2; weight, m/s; volume, W/m^3	Eq. (5.2.2)
T_B; s_B	body temperature, K; body surface area, m^2	Sect. 5.2
j_B	metabolic rate per unit body surface area, W/m^2	Sect. 5.2
h_B; l_B	heat conductivity, Wm^{-1}K^{-1}; thickness of the insulating body layer, m	Sect. 5.2
$j_{e\,min}$; $j_{e\,max}$	minimum and maximum metabolic rate per unit body projection area for endothermic animal, W/m^2	Sect. 5.2
P_l^+; p_l^+	net primary productivity in units of live mass, kg m^{-2} year^{-1}; in power units, W/m^2	Eqs. (5.3.1) and (5.3.6)
k_T	transpiration coefficient: amount of moisture transpired per unit live mass of plant production, dimensionless	Eq. (5.3.7)
E	total evaporation rate, m/year	Eq. (5.3.7)
α_T	ratio of transpiration to total evaporation	Eq. (5.3.7)
η_T	transpiration efficiency: share of solar energy spent on transpiration, dimensionless	Eq. (5.3.8)

Symbol	Definition and Units	First Use
E_{max}	global average maximum evaporation rate when all the solar energy is spent on evaporation, m/year	Eq. (5.3.8)
L_w	latent heat of evaporation for water, J/kg	Eq. (5.3.9)
η_p	photosynthesis efficiency, dimensionless	Eq. (5.3.9)
N	number of mutually uncorrelated parts of local ecosystem	Eq. (5.4.1)
κ	breach: relative difference of net primary production and organic destruction	Sect. 5.4, see Eq. (4.3.2)
L_c	size of local ecosystem, m	Eq. (5.4.1)
r^+	average correlation radius for plants, m	Eq. (5.4.1)
n^+	number of plant species in the community determining the main part of net primary productivity	Eq. (5.4.2)
β	share of consumption of the net primary production by an animal of a given body size, dimensionless	Eq. (5.5.1)
n	number of equally represented species in the community corresponding to a given body size	Eq. (5.5.1)
β_i	consumption share of net primary production for species i, dimensionless	Eq. (5.6.2)
Δz	relative interval of body size, dimensionless	Eq. (5.6.2)
z	decimal logarithm of body size	Eq. (5.6.2)
$\beta(z)$	community consumption share per unit relative body size interval (destructivity size spectrum), dimensionless	Eq. (5.6.2)
β_l	share of consumption by an individual of body size l averaged over all the species in the community, dimensionless	Sect. 5.6
B	biomass of individual of body size l, averaged over all the species in the community, kg/m^2	Sect. 5.6
L	biomass layer thickness of individual of body size l, averaged over all the species in the community, m	Sect. 5.6
d_0	leaf area index, dimensionless	Table 5.1

Symbol	Definition and Units	First Use
$d \equiv \frac{L}{l}$	projection area index for heterotrophs, dimensionless	Sect. 5.6
u	speed of animal movement, m/s	Eq. (5.7.1)
$q(u)$; $A(u)$	metabolic rate, W; total activity, dimensionless, of an animal moving at speed u	Eq. (5.7.2)
$a; b$	net moving activity and readiness, dimensionless	Eq. (5.7.2)
u_0	speed for movement when $a = 1$, m/s	Eq. (5.7.2)
$t_a; T$	duration of activity state; duration of day, s	Sect. 5.7
x_a	relative duration of activity state for animal, dimensionless	Eq. (5.7.3)
L_T; $L_{T\,\max}$	daily travelling distance and its maximum, m	Eq. (5.7.4)
$u_a \approx u_0$	available speed of animal movement, m/s	Eq. (5.7.5)
ρ_c	air density, kg/m^3	Sect. 5.8
$l \equiv \left(\frac{m}{\rho}\right)^{1/3}$	effective body size of mobile animal, m	Eq. (5.8.1)
γ_{tot}; γ; γ_c	total, ground and air dissipation coefficients, dimensionless	Eqs. (5.8.2) and (5.8.3)
λ_0	basal metabolic rate per unit body weight, m/s	Eq. (5.8.5)
α	efficiency of transformation of metabolic power into the power of mechanical movement, dimensionless	Eq. (5.8.5)
ε	energy cost of moving unit weight through unit distance, dimensionless	Eq. (5.8.6)
$u_{\max}$	maximum speed of running recorded for animal of body size l, m/s	Eq. (5.8.7)
k^2	Froude number for maximum speed of running independent of body size l, dimensionless	Eqs. (5.8.4) and (5.8.7)
$B_l; L_l$	vegetation biomass, kg/m^2; thickness of its layer, m	Sect. 5.9
B_L	part of vegetation biomass consumed by animal of body size l, kg/m^2	Sect. 5.9
$B_{L\,\min}$	minimum value of B_L	Eq. (5.9.4)
$\beta_L = \frac{B_L}{B_l}$	share of vegetation biomass consumed by animal of body size l, dimensionless	Eq. (5.9.1)

Symbol	Definition and Units	First Use
$\beta_{L\,\min}$	minimum value of β_L	Eq. (5.9.3)
u_n	speed necessary to support the animal's existence, m/s	Eq. (5.9.2)
S	area of animal's feeding ground (home range), m^2	Sect. 5.10
τ_S	time in which the animal makes a round of its feeding ground, years	Eq. (5.10.1)
Λ	metabolic rate per unit body volume in units of living mass, kg m^{-3} year^{-1}	Eq. (5.10.2)

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