THE BIOLOGICAL ROLE OF CARBON DIOXIDE

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CARBON dioxide is found in all environments in which life occurs. Although some of the large organisms may produce sufficient CO_2 in their metabolism that they are not dependent upon external CO_2, and may be independent of external P_{CO_2} so long as it is low (< 0.01 to 0.05 atmospheres), there is little doubt that all cellular and multicellular organisms require CO_2.

Although the first organisms may have evolved in a world of methane and organic compounds,[1] CO_2 has been part of the aquatic and atmospheric life for well in excess of a billion years.[2] It is not surprising, therefore, to find that CO_2 is an active partner in many aspects of metabolism of all organisms.

During the nineteenth century and the early decades of the twentieth century, it was assumed that the only metabolic role of CO_2 was its utilization in the metabolism of green plants in the light, and that other organisms (nongreen plants, bacteria, animals) produced CO_2 in irreversible reactions. This view, which is still part of much teaching, persisted in spite of the ever-increasing evidence in human physiology of the complex relation between CO_2 of tissues and the external environment. When Rockwell[3] and Rockwell and Highberger[4] reported in 1921 and 1927 that certain bacteria, yeasts, and molds required CO_2 for growth and incorporated the carbon into carbon compounds, their results were ignored or denied.

In 1936 Wood and Werkman[5] showed that the conversion of carbohydrates to propionic acid by the propionic bacteria occurred with the incorporation of CO_2. This was confirmed later[6, 7] through the use of carbon isotopes. Work done since 1940 has made it clear that the reactions of CO_2 release are reversible, and that carbon dioxide may be liberated or absorbed, depending upon conditions, in a wide variety of organisms. Carbon dioxide incorporation has largely been obscured in nongreen plants by the excess CO_2 production, but isotopic methods have made it possible to show incorporation in spite of excess production, and to demonstrate that in many (probably all) organisms certain biochemical pathways are necessarily coupled to CO_2 utilization. Though the reduction of CO_2 to carbohydrates in photosynthesis depends upon the energy of sunlight, as we shall show below, the actual pathways of CO_2 incorporation occur in nonphotochemical reactions.

CARBON DIOXIDE AND METABOLISM

Fortunately, the evolution of biological systems has been such that in spite of great morphological diversity the metabolic systems are surprisingly similar for very dissimilar organisms. This is illustrated in the metabolism of CO_2.

In cellular respiration, many oxidative steps do not directly produce CO_2, as biological oxidation occurs primarily by electron transfer over a series of oxidation-reduction catalysts (the respiratory enzymes and coenzymes) or by dehydrogenation. Carbon dioxide is produced primarily in the decarboxylation of α-keto acids, though these decarboxylations are often coupled to oxidative steps. Thus, we find the citric acid cycle, the Embden-Meyerhof fermentation pathway, and the pentose-phosphate pathway operative in such dissimilar organisms as yeasts and bacteria, mammals, and in higher plants.

Succulent plants (Bryophyllum, cacti, etc.), which produce organic acids (primarily malic acid) in the dark from carbohydrates, do so in oxidative metabolism and with CO_2 absorbed from the environment.[8] Until this was discovered it had been impossible to write balanced equations showing the conversion of sugars to malic acid. This problem is resolved by the incorporation of CO_2. The nonphotochemical reduction of CO_2 requires energy, but here the energy is furnished by the oxidation of organic compounds, through the intermediate action of energy stored in adenosine triphosphate and reduced pyridine nucleotides. In most cases, the production of CO_2 is far greater than the amount fixed, but in the succulent plants, in the dark, there is no CO_2 production but there is a net utiliza-

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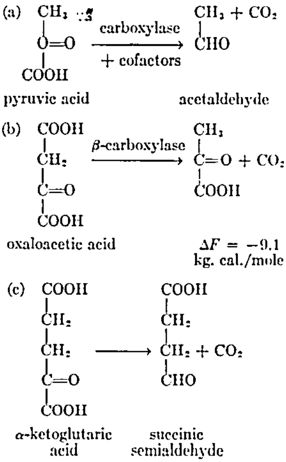
tion of carbohydrate and the energy released in the oxidation of sugars to organic acids is used in the fixation of CO_2.

That the reduction of CO_2 to the level of carbohydrates occurs in photosynthetic reactions without the direct participation of light is clear from the following observations. McAlister[9] found that in green plants undergoing a steady photosynthesis, after a sudden interruption of the light, there is a continued absorption of CO_2 for 90 to 170 seconds. Calvin, *et al.*[10] then demonstrated that if radioactive CO_2 is furnished to plants in the dark, after a prior light period, the CO_2 is reduced to the level of carbohydrates, the amount reduced being equal to that reduced in one minute of photosynthesis; no such reduction occurred in comparable plants lacking the prior light period. It was thus clear that during the light some compounds were produced that could reduce CO_2 to carbohydrates. The energy for CO_2 reduction is furnished by the radiant energy of the light, but the energy is passed on by catalytic substances acting in a cyclical manner. These results made it possible to separate the photochemical aspects of photosynthesis from the enzymatic steps of CO_2 reduction.

Earlier work by Hill[11] had already demonstrated that the photolysis of water, with the liberation of O_2, was independent of CO_2 reduction. The work of Strehler,[12] Frankel,[13] and of Arnon[14] has shown that the reduction of CO_2 occurs in nonphotochemical reactions through reaction with adenosine triphosphate and a hydrogen donor (perhaps reduced pyridine nucleotides). The adenosine triphosphate and the reducing agent are formed during the photochemical reactions. Thus the final stage of CO_2 reduction in photosynthesis is a series of reactions similar to those recognized as part of the carbohydrate metabolism of nonphotosynthetic organisms.

Though we cannot recount here details of the reactions of carbohydrate metabolism, we can give a few of them and so show the reversible entrance of CO_2 into metabolism.

The release of CO_2 may occur in one of several decarboxylation reactions, a few of which are illustrated below:



$$(a)\quad \begin{array}{c} CH_3 \\ | \\ O{=}O \\ | \\ COOH \end{array} \xrightarrow[+\text{ cofactors}]{\text{carboxylase}} \begin{array}{l} CH_3 + CO_2 \\ | \\ CHO \end{array}$$

pyruvic acid acetaldehyde

$$(b)\quad \begin{array}{c} COOH \\ | \\ CH_2 \\ | \\ C{=}O \\ | \\ COOH \end{array} \xrightarrow{\beta\text{-carboxylase}} \begin{array}{l} CH_3 \\ | \\ C{=}O + CO_2 \\ | \\ COOH \end{array}$$

oxaloacetic acid $\Delta F = -9.1$ kg. cal./mole

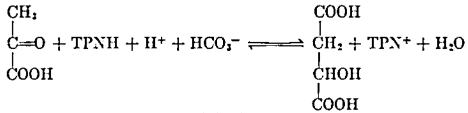
$$(c)\quad \begin{array}{c} COOH \\ | \\ CH_2 \\ | \\ CH_2 \\ | \\ C{=}O \\ | \\ COOH \end{array} \longrightarrow \begin{array}{l} COOH \\ | \\ CH_2 \\ | \\ CH_2 + CO_2 \\ | \\ CHO \end{array}$$

α-ketoglutaric acid succinic semialdehyde

The actual reactions are far more complex than illustrated. The equilibrium for these reactions lies far on the side of CO_2 release, and, in fact, such reactions were considered irreversible.

Wood, *et al.*[7] were able to demonstrate, with isotopic CO_2, that reaction (b) is reversible, *i.e.*, that isotopic C introduced as CO_2 could be found in the carboxyl group of organic acids. Though the reversal of this particular reaction may not be physiologically of great importance, these experiments changed our whole outlook on the biological activity of CO_2.

Ochoa[15] found a reaction of considerable interest, the reversible incorporation of CO_2 into malic acid:

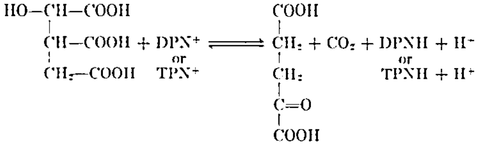


$$\begin{array}{l} CH_3 \\ | \\ C{=}O + TPNH + H^+ + HCO_3^- \\ | \\ COOH \end{array} \rightleftharpoons \begin{array}{l} COOH \\ | \\ CH_2 + TPN^+ + H_2O \\ | \\ CHOH \\ | \\ COOH \end{array}$$

$\Delta F = 3.0$ kg. cal./mole
TPNH = reduced triphosphopyridine nucleotide
TPN^+ = oxidized triphosphopyridine nucleotide.

This reaction could be followed on the spectrophotometer, because of high absorption of TPNH at 340 mμ. The reaction is mobile, and may be readily shifted from right to left, or *vice versa*, by varying the concentration of the reactants. Vennesland and co-workers[16] found a similar enzyme in higher plants. The energy for the carboxylation can be thought of as being furnished by the reduced TPNH.

In similar fashion, reversible reactions are known for isocitrate and α-ketoglutaric acids:



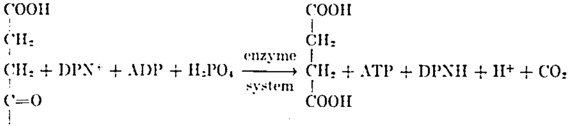
$$\begin{array}{l}\mathrm{HO{-}CH{-}COOH}\\ \quad|\\ \mathrm{CH{-}COOH}\\ \quad|\\ \mathrm{CH_2{-}COOH}\end{array} + \begin{array}{c}\mathrm{DPN^+}\\ \text{or}\\ \mathrm{TPN^+}\end{array} \rightleftharpoons \begin{array}{l}\mathrm{COOH}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{C{=}O}\\ |\\ \mathrm{COOH}\end{array} + \mathrm{CO_2} + \begin{array}{c}\mathrm{DPNH + H^+}\\ \text{or}\\ \mathrm{TPNH + H^+}\end{array}$$

isocitric acid α-ketoglutaric acid

DPN+ and DPNH represent oxidized and reduced diphosphopyridine nucleotides.

Enzymes are known which react either with TPN or DPN, and this reaction is reversible, allowing CO_2 incorporation or release, depending upon the concentration of the reactants.

The decarboxylation of α-ketoglutaric acid is of some interest:



$$\begin{array}{l}\mathrm{COOH}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{C{=}O}\\ |\\ \mathrm{COOH}\end{array} + \mathrm{DPN^+} + \mathrm{ADP} + \mathrm{H_3PO_4} \xrightarrow[\text{system}]{\text{enzyme}} \begin{array}{l}\mathrm{COOH}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{COOH}\end{array} + \mathrm{ATP} + \mathrm{DPNH} + \mathrm{H^+} + \mathrm{CO_2}$$

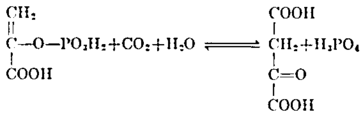
succinic acid

Here, the enzyme system involves at least two enzymes and coenzyme A. The reaction may proceed from left to right or the reverse.

We are interested in these reactions because they are an important part of carbohydrate degradation, but they are all responsive to the P_{CO_2} and may serve, in part, for CO_2 fixation in nonphotosynthetic reactions.

There is some doubt whether any of these reactions is of importance in photosynthesis, since they all require an appreciable P_{CO_2} while photosynthesis occurs at high velocity at $P_{CO_2} = 3 \times 10^{-4}$ atmosphere and at maximum velocity at 1 to 2×10^{-3} atmosphere.

The hydrolysis of a phosphate bond may yield energy that can be used for the addition of CO_2 as a carboxyl group:

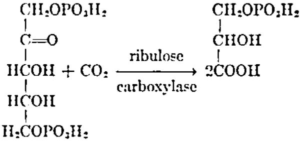


$$\begin{array}{l}\mathrm{CH_2}\\ \|\\ \mathrm{C{-}O{-}PO_3H_2}\\ |\\ \mathrm{COOH}\end{array} + \mathrm{CO_2} + \mathrm{H_2O} \rightleftharpoons \begin{array}{l}\mathrm{COOH}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{C{=}O}\\ |\\ \mathrm{COOH}\end{array} + \mathrm{H_3PO_4}$$

phosphoenol pyruvate oxaloacetic acid

This reaction is catalyzed by phosphoenol pyruvic carboxylase.

Perhaps the most startling result was the discovery that in photosynthesis a 5-carbon phosphate sugar gave rise to two molecules of phosphoglyceric acid:



$$\begin{array}{l}\mathrm{CH_2OPO_3H_2}\\ |\\ \mathrm{C{=}O}\\ |\\ \mathrm{HCOH}\\ |\\ \mathrm{HCOH}\\ |\\ \mathrm{H_2COPO_3H_2}\end{array} + \mathrm{CO_2} \xrightarrow[\text{carboxylase}]{\text{ribulose}} 2\begin{array}{l}\mathrm{CH_2OPO_3H_2}\\ |\\ \mathrm{CHOH}\\ |\\ \mathrm{COOH}\end{array}$$

D-ribulose-1,5-diphosphate 3-phosphoglyceric acid

This enzyme, ribulose carboxylase, appears to be limited to the chloroplasts, and is presumably limited to photosynthetic activity. The phosphoglyceric acid may then undergo reduction to triosephosphates through the energy stored in ATP and reduced nucleotides. The trioses not only can be converted to sugars and starches but, through a series of cyclical

TABLE 1

CARBON ON THE EARTH *

	As CO_2	As C	g./cm.^{2} †
	10^{20} g.		
Atmosphere	0.0233	0.00635	0.124
Fresh water	0.009	0.0024	0.047
Seas	1.29	0.352	6.9
Biospere	0.145	0.04	0.784
Rocks			
As carbonates	674.0	184.0	3,600.0
Other forms of C	246.0	67.0	1,313.0
Fossil fuels	0.27	0.73	14.3
Total	921.74	250.93	

* Data from Rubey.[18]

† g./cm.^{2} earth's surface, calculated on basis of earth's surface = 5.1 × 10^{18} cm.^{2}

reactions, regenerate ribulose diphosphate to keep the process functioning. If one follows the reactions through in detail, it appears that three molecules of ATP and two of reduced TPNH (or DPNH) are required for each molecule of CO_2 reduced to the level of a carbohydrate.

Carbon dioxide has many physiological effects, aside from its role in photosynthesis. We will omit consideration of its role in the mammalian blood system and its effect in the regulation of the frequency and depth of breathing. Loomis [17] has summarized some of the actions of P_{CO_2} as a regulator of embryonic growth. Free CO_2 must act, either by changing the *p*H or participating in chemical reactions, where the equilibrium (or steady state level) is highly sensitive to P_{CO_2}.

The reactions outlined above may not be the critical reactions, but the biochemistry of CO_2 has proceeded far enough for us to recognize that CO_2 is a highly reactive cellular metabolite. We may expect that the understanding of the individual reactions in which CO_2 participates may furnish the understanding of its complex physiological role in the cells and tissues of bacteria, fungi, and higher plants and animals.

INTERNAL ENVIRONMENT AND CARBON DIOXIDE

Carbon dioxide in the atmosphere is at very low level, a P_{CO_2} of about 3.2 × 10^{-4} atmosphere (0.23 mm.). The leaves of higher plants may function at this low CO_2 pressure. Many microorganisms may be in diffusion equilibrium with environmental CO_2, but because of ecological environments (whether soils, waters, or the tissues of higher animals or plants) the P_{CO_2} is usually from 10 to 200 times that of the atmosphere. We recognize that P_{CO_2} of blood and mammalian tissues is far from diffusion equilibrium with the atmosphere, but it is not so generally recognized that this is also true of plant stems, roots, fruits, and most metazoans. Diffusion equilibrium is apparently the exception in the biological world.

Therefore a clear distinction is required between the internal and external environments. This may be illustrated by the problem of mammalian tissue cultures.[17] If tissue cultures are in mass and in a closed system, the metabolic activity will raise the P_{CO_2}. However, if mammalian tissues are exposed to air, CO_2 will escape from the tissue, which was in prior equilibrium with blood, and the *p*H may rise and the tissue die. At least as early as 1937 this problem was faced and, on theoretical grounds, the proposal was made and adopted to use 5 per cent CO_2 in air when a gaseous stream was passed over a tissue culture in a bicarbonate-containing medium.

ENVIRONMENTAL CARBON DIOXIDE

Carbon is the sixth most abundant cosmic element, though it is less abundant in the outer crust of the earth than the inner. The figures in table 1 are from Rubey [18] and are to be considered as estimates. The total carbon of the lithosphere, hydrosphere and atmosphere is approximately × 51 × 10^{20} g. (or 251 × 10^{14} metric tons). This corresponds to 921 × 10^{20} g. of CO_2. The CO_2 of the atmosphere is about 1/40,000 of the total, and the total CO_2 of the seas (CO_2, HCO_3^-, and $CO_3^=$) is 55 times the amount of the atmosphere. It is clear that the greatest mass of the earth's carbon is locked in the carbonate of rocks.

The Atmosphere. Though we normally consider the CO_2 content of the atmosphere as constant, and usually assign it a value of 0.03 per cent, considerable variations from this value occur. Though the P_{CO_2} decreases with altitude, the percentage composition is not markedly affected by altitude[19] and a value of 0.029 ± 0.002 per cent was indicated by data from the rocket Explorer II at 72,000 feet.[20] However, Buch[21] found that over the North Atlantic the CO_2 in air in equilibrium with the sea was 0.0329 per cent, while in arctic the average was 0.0308 per cent, with values as low as 0.015 per cent being recorded. In general, a decrease in the CO_2 content of sea water and in air is found from tropical to northern seas.

Industrial and biological activity can cause considerable variation in atmospheric CO_2. This is most marked on days when the wind velocity is below one to two miles per hour. For example, Chapman, Gleeson and Loomis[22] have followed the diurnal variation of atmospheric CO_2 in an Iowa corn field at one and 152 m. above the ground. On a calm day (wind one to two miles per hour) the peak CO_2 was found at 4:00 A.M. at 1.0 m. to be 0.0477 per cent. By 7:00 A.M. this had fallen to 0.03 per cent, and the minimum of 0.022 per cent occurred at 1:00 P.M. with a rise to 0.03 per cent just after sunset. At 152 m., the changes were smaller, but even at this elevation the photosynthesis lowered the CO_2 level during daylight hours. An Iowa corn field may remove 200 pounds of CO_2 per acre per day (maximum value of 400 pounds). This corresponds to the total CO_2 in a column of air 333 m. Easily detectable decreases during sunny hours were determined even when the wind was eight miles per hour. The increase during the night was probably due largely to plant respiration and in part to respiration of soil organisms.

Fresh Water. Lakes and rivers constitute a small part of the earth's surface, but they are an important habitat for many organisms. Hutchinson[23] has given an excellent account of the chemical and physical properties of fresh waters. The composition of lake water is not a constant with depth, and there are also marked seasonal changes.

TABLE 2

THE APPARENT DISSOCIATION CONSTANT FOR CARBONIC ACID

Temperature (Centigrade)	K_a	pK_a
0	2.65×10^{-7}	6.58
5	3.04×10^{-7}	6.52
10	3.43×10^{-7}	6.46
15	3.80×10^{-7}	6.42
20	4.15×10^{-7}	6.38
25	4.45×10^{-7}	6.35

TABLE 3

THE PROPORTIONS OF CO_2, HCO_3^-, AND $CO_3^=$ IN WATER AT VARIOUS pH VALUES AND 15 C.

pH	CO_2	Total Free HCO_3^-	$CO_3^=$
4	0.996	0.004	1.25×10^{-9}
5	0.962	0.038	1.20×10^{-7}
6	0.725	0.275	0.91×10^{-5}
7	0.208	0.792	2.60×10^{-4}
8	0.025	0.972	3.20×10^{-4}
9	0.003	0.996	0.031
10	2×10^{-4}	0.757	0.243

Carbon dioxide in fresh waters will exist as dissolved CO_2, H_2CO_3, HCO_3^-, and $CO_3^=$. We can consider the following reactions as occuring:

$$\begin{aligned} CO_2 + H_2O &\rightleftharpoons H_2CO_3 \\ H_2CO_3 &\rightleftharpoons H^+ + HCO_3^- \\ HCO_3^- &\rightleftharpoons H^+ + CO_3^= \end{aligned}$$

The dissociation of carbonic may be readily formulated:

$$K_{H_2CO_3} = \frac{(H^+)(HCO_3^-)}{(CO_2 \text{ total})}$$

The difficulty arises because the concentration of H_2CO_3 is not known with precision. It has been reported as 1.105 to 0.56 per cent of the free CO_2. Berg and Patterson[24] have given the value of $K_{H_2CO_3}$ as $1.32 \pm 0.5 \times 10^{-4}$ at 25 C.

The problem is avoided by formulating the equation as follows:

$$K_a = \frac{(H^+)(HCO_3^-)}{(CO_2 \text{ total})}$$

where CO_2 is total analytically determined CO_2. The equation is valid for very dilute solutions, and K_a may be considered the apparent dissociation constant. Its value from Horned and Davis[25] is given in table 2. The constant is not independent of the salt content of the waters; in lakes and rivers the divalent ions predominate, and the constant can be

TABLE 4

CARBON DIOXIDE CONTENT OF SELECTED SOILS

	Percentage CO_2 in Air Spaces	
	At 6-inch depth	At 18-inch depth
Arable land (manured)	0.34	0.5
Arable land (not manured)	0.34	0.45
Grassland	1.46	1.64
Water-logged soil	3.9 to 9.1	

corrected for dissolved salts as follows:

$$pK_a' = pK_a - 0.53\sqrt[3]{m}$$

where m = molarity of the solution.

In fresh waters where the *p*H is usually below 8.0 we are rarely concerned with the second dissociation constant of CO_2. Table 3, from Hutchinson,[23] is of some interest in showing the distribution of CO_2 in various forms for fresh waters.

The situation in lakes is complex, and the interested reader is referred to Hutchinson.[23] The CO_2 content will depend in part upon equilibrium with the atmosphere, the withdrawal of CO_2 in photosynthesis, the addition by respiration, and the addition of acids or alkali from soil waters. The effect of temperature on CO_2 solubility cannot be ignored. Many lakes will be stratified, with high CO_2 content in lower levels.

Soil Carbon Dioxide. Russell and Appleyard[26] have studied the CO_2 content of agricultural soils. Table 4 has been constructed from their values. Though the composition of the gases of soils is highly variable, and will depend upon water content, total organic matter, and temperature, it is to be recognized that soil organisms and the roots of plants live in environments where the CO_2 content is 10 to 100 times that of the atmosphere.

The Seas. The surface waters of the open oceans in temperate latitudes is constant. The sodium chloride content will be about 3.5 g./l., expressed as salinity (S) per cent 35. The *p*H will vary from approximately 8.1 to 8.3. The total CO_2 (CO_2, HCO_3^-, $CO_3^=$) is approximately 46 ml./l.

The composition of sea water is shown in table 5. The total CO_2 content and free CO_2 of sea water, in relation to *p*H, are shown in table 6. Melting arctic ice and large rivers will dilute sea water, and, as the salinity is decreased, the constants affecting the dissociation of CO_2 are also changed.

The dissociation constants of carbonic acid change with the salt content, temperature, and pressure. Buch[27] has constructed tables giving the values of K_a' and K_{a_2}' at different temperatures and salinity; these tables have been reproduced by Harvey.[28] The effect of salt on the constants is shown below:

	Water	Sea Water (S per cent 35)
	Temperature 15 C.	
pK_{a_1}'	6.43	6.04
pK_{a_2}'	10.43	9.07

Since surface sea waters have a *p*H of 8.0 to 8.3, the bicarbonate/carbonate system will be dominant.

The CO_2 content of surface waters is modified by biological activity. The phytoplankton absorb free CO_2 in photosynthesis, and this results in a decreased P_{CO_2} and a rise in *p*H. The CO_2 is partially replaced by the conversion of bicarbonate to carbonate:

$$\begin{tikzcd}
2\,NaHCO_3 \arrow[r, shift left] & Na_2CO_3 + H_2CO_3 \arrow[l, shift left] \arrow[d, shift left] \\
 & H_2O + CO_2 \arrow[u, shift left]
\end{tikzcd}$$

TABLE 5

COMPOSITION OF SEA WATER AT 15 C., S per cent 35, *p*H 8.15

	g./kg.	g./l.	Molarity
Total salts	35.1	36	0.558
Sodium	10.77	11.1	0.483
Magnesium	1.3	1.33	0.0547
Calcium	0.409	0.42	0.0105
Potassium	0.388	0.39	0.00997
Strontium	0.01	0.01	0.00011
Chloride	19.37	19.8	0.558
Sulfate	2.71	2.76	0.0287
Bromide	0.065	0.066	0.00083
Boric acid			
H_3BO_3	—	0.021	0.00033
$H_2BO_3^-$	—	0.0048	0.00008
Total CO_2	—	46.1 ml./l.	0.00209
CO_2	—	0.29 ml./l.	0.0000128
HCO_3^-	—	—	0.00185
$CO_3^=$	—	—	0.00023
O_2	—	5.8 ml./l.	0.00026

TABLE 6

CARBON DIOXIDE OF SEA WATER AT 15 C., S PER CENT 35

*p*H	7.1	7.8	8.0	8.1	8.2	8.3	8.4	8.5
Total CO_2								
moles/l. × 10^5	238	235	216	211	206	199	191	183
ml./l.	53.3	52.6	48.4	47.3	46.1	44.6	42.8	41
P_{CO_2}								
atmosphere × 10^5	230	85	50	39	29	22	15	12
CO_2								
moles/l. × 10^5	8.94	3.31	1.95	1.57	1.13	0.86	0.58	0.47
ml./l.	2.0	0.74	0.44	0.34	0.25	0.19	0.13	0.1

In northern seas, the rapid growth of diatoms in the spring months results in a photosynthetic level which exceeds the combined respiration of algae, bacteria, and animals, with a resulting increase of *p*H and a fall of P_{CO_2}. In the winter months respiration may exceed photosynthesis, with an increasing P_{CO_2} and a fall of *p*H.

THE SEA AS A REGULATOR OF CARBON DIOXIDE

As early as 1880, Schlösing[29] proposed that the sea was a regulator of atmospheric CO_2. The seas contain 55 times as much CO_2 as does the atmosphere. Krogh[30] and more recently Buch[31] have studied the equilibrium between atmospheric CO_2 and sea water. An excess of atmospheric CO_2 should result in absorption by the sea, with a resulting decrease in *p*H and a dissolution of $CaCO_3$. Rubey[18] has calculated what would happen if the CO_2 content of air was increased fivefold, to 0.015 per cent (after equilibrium with the sea). To raise the level in the atmosphere fivefold would increase the total atmospheric CO_2 from 2.33×10^{18} g. to 11.65×10^{18} g. To increase the CO_2 of the atmosphere by this amount would require the addition of 81×10^{18} g., of which some 71.7×10^{18} g. would have dissolved in the sea. This increased CO_2 in the sea would result in the dissolution of $CaCO_3$, the dissolution of lime rods would have added 62×10^{18} g. of CO_2 and the final *p*H would be 7.8.

There is a belief[28] that the CO_2 content of the atmosphere has increased about 10 per cent since 1900. Such an increase would mean 2.2×10^{17} g. of CO_2 in the atmosphere and, if equilibrium had been reached with the sea, 90 per cent of the CO_2 would be expected to have been absorbed by the sea or, in other words, there would have been a total increase of 2.2×10^{18} g. This corresponds to 8.5×10^{11} metric tons of coal. The 2.2×10^{17} g. of CO_2 in the atmosphere is not out of order with expected industrial production, as Callendar[32] estimated in 1940 an industrial production of 43×10^{15} g. of CO_2 per year and for sixty years this is 2.68×10^{17} g. in comparison with a suggested atmospheric increase of 2.2×10^{17} g. The industrial production of CO_2 is inadequate to cause an increase of 10 per cent CO_2 in the atmosphere if nine-tenths of the CO_2 has entered the seas. Either the increase has not in fact occurred, or equilibrium with the seas has not been established. One would also expect an increase in atmospheric CO_2 to result in an increase in photosynthesis and an increased locking up of CO_2 in the biosphere.

GEOLOGICAL ORIGIN

Urey[1] and Kuiper[33] have proposed that the initial earth had a reducing atmosphere of methane, ammonia and hydrogen. Carbon dioxide is not stable in a hydrogen atmosphere. The gravitational field of the earth cannot permanently hold a hydrogen atmosphere, and hydrogen would escape except as it is bound in water, methane, metal hydrides and ammonia. The CO_2 of the atmosphere may have had its origin from volcanos and hot springs.[2] Though the rate of production is low (3 to 7×10^{13} g. per year), only about 0.04 to 0.07 per cent of the current photosynthetic rate, the current

TABLE 7[1]

RATE OF PHOTOSYNTHESIS ON LAND

	Area, 10^{16} cm.^{2}	Areal Fixation, mg./cm.^{2} year		Total Fixation for Whole Area, 10^{15} g./year	
		C	CO_2	C	CO_2
Forest	44	20	73.3	8.8	32.3
Cultivated	27	16	58.6	4.3	15.8
Grassland	31	6	22	1.9	7
Desert	24	0.5	1.8	0.1	0.2
Total	126	12	44	15.1	55

[1] From Hutchinson.[2]

atmosphere CO_2 could be produced in 60,000 years and that of the seas and atmosphere in a few million years. These are geologically very short times. On the other hand, life may have had its origin in an anaerobic world, with little or no CO_2 and the CO_2 may be of biological origin. Though one considers CO_2 to be produced by living organisms by the use of O_2 in respiration, chemical mechanisms for the degradation of organic compounds without utilization of oxygen are possible.

We do not know which gas occurred first, O_2 or CO_2. Oxygen could have been first produced by the photochemical decomposition of water at high altitudes:

$$H_2O + h\nu \longrightarrow H_2 + O$$
$$O + O \longrightarrow O_2.$$

The hydrogen would then be lost to the earth. Kuiper[33] has calculated that the rate of this process could produce our atmosphere in 5 × 10^8 years. This is a very low rate compared with present-day photosynthesis, since the estimate of photosynthetic rates indicates an O_2 production of 55 × 10^{15} g. per year,[2, 34] or the atmospheric O_2 of 12 × 10^{20} g. could be produced in 22,000 years, and even a rate of one-fifth of this would form our O_2 in 100,000 years.

Thus the primitive O_2 and CO_2 may have had a nonbiological origin, but once photosynthetic life was firmly established the activities of organisms must have become dominant in the biological evolution of O_2, water, and CO_2.

THE CIRCULATION OF CARBON DIOXIDE

Generations of students have been taught that the respiration of animals balances the photosynthesis of plants. Such statements are usually in nonquantitative terms, and frequently ignore the role of plant respiration. Several workers have made efforts to estimate the quantity of photosynthesis. Table 7, from Hutchinson,[2] makes a respiratory correction for plants, and arrives at an over-all rate for land plants of 73 ± 18 × 10^{15} g. CO_2 per year.

The respiratory component is made up of the respiration of higher plants, approximately 20 per cent, of higher animals, and of soil organisms (bacteria, fungi, protozoa and soil invertebrates). The human contribution can be approximated; if we assume a population of 2.7 × 10^9 and a daily calorie intake of 2500 kg. cal., the yearly CO_2 production is 1.0 ± 0.2 × 10^{15} g. CO_2. Thus human respiration may account for 1.4 per cent of land photosynthesis.

In a mature forest, the respiration of material on and within the soil will nearly balance the net photosynthesis (total photosynthesis minus respiration of the higher plants). The total CO_2 added by respiration of soil organisms may be 80 per cent of total photosynthesis under these conditions, whereas for agricultural land it may be only half of this. What percentage of the respiration is to be ascribed to bacteria, fungi, invertebrates, and higher plant roots is unknown.

TABLE 8 *

TOTAL METABOLISM OF THE EARTH

	CO_2 Used	O_2 Produced
Ocean	462 ± 303 × 10^{15} g./yr.	336 ± 218 × 10^{15} g./yr.
Land	73 ± 18 × 10^{15} g./yr.	53 ± 15 × 10^{15} g./yr.
Whole earth	535 ± 311 × 10^{15} g./yr.	389 ± 231 × 10^{15} g./yr.
Unit area	105 ± 63 mg./cm.^{2}/yr.	76 ± 45 mg./cm.^{2}/yr.

* From Hutchinson.[2]

Though the photosynthesis of certain areas of the seas may rival or exceed that of agricultural land,[2] an evaluation of the total photosynthesis is difficult. Riley[31] has given estimates, which are used as the basis for the information in table 8. Though there is uncertainty concerning the absolute magnitude, it is probably safe to assume that photosynthesis of land plants constitutes about one-fifth of the total, the remaining four-fifths occurring in the open seas. The respiration of marine animals probably comes far closer to a balance of marine photosynthesis than does that of land animals balance photosynthesis of land organisms. Though the productivity of the seas may be limited by light or temperature, during part of the year, the rapid growth of diatoms depletes the surface waters of nitrates, phosphates, and silicates. It is doubtful if CO_2 ever limits the growth of marine life. The rapid circulation of marine C through living organisms is limited to surface waters (0 to 400 m.) and the slow mixing in the seas means that the C of the ocean deeps moves through the cycle of life at a very low rate.

CONCLUSIONS

All life appears to be dependent upon CO_2, indirectly through the role of CO_2 in photosynthesis and directly as CO_2 is an essential part of the organism's own biosynthetic pathways and a determinant in development and differentiation. Carbon dioxide is part of the internal environment of all organisms and many small organisms which are unable to satisfy their needs by endogenously produced CO_2 are dependent upon external CO_2. Larger organisms are rarely in diffusion equilibrium with their environments for CO_2.

The CO_2 contents of the environments are varied. Though the CO_2 content of air is considered a constant, it may change by 100 per cent within a day over agricultural land. The CO_2 content of soils and waters, though far from constant, is frequently strikingly above that of the air. In micro-environments the activity of organisms plays an important role in the determination of CO_2 levels.

Though the quantity of CO_2 appears large, the atmospheric CO_2 passes through living organisms once in ten years. The quantities in the seas and carbonate rocks appear to be tremendous, but in terms of biological activity over a period of one to two billion years these sums are not large.

The origin of life and its evolution cannot be understood without considering the geochemistry of the early earth and the recognition that the physiological functions found in advanced organisms are in part derived from mechanisms established by evolution in more primitive organisms. Nowhere is this more clearly established than in the relation of organisms to CO_2.

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