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Tables

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Age (billion years ago)	Surface temperature	Organism	Upper temp limit (°C)
3.5 – 3.8	70-100	Extreme theromophile	100+
2.6-3.5	60-70	Cyanobacteria	73
0.7-2.6	50-60	Thermophilic Eukarya	55
0.4-0.7	45-50	Complex animals and plants	~40
0.2-.04	20-45		
0-0.2	15-20		

Net primary productivity of biosphere

Ecosystem	area (10^6 km^2)	Mean production (g/m^2/y)	Total production (10^9 t/y)	mean biomass (kg/m^2)
Tropical rain forest	17.0	2200	37.4	45
Tropical seasonal forest	7.5	1600	12.0	35
Temperate evergreen	5	1300	6.5	35
Temperate deciduous	7	1200	8.4	30
Boreal forest	12	800	9.6	20
Woods and shrubs	8.5	700	6.0	6
Savanna	15	900	13.5	4
Grassland	9	600	5.4	1.6
Tundra	8	140	1.1	0.6
Desert	18	90	1.6	0.7
Extreme desert	24	3	0.07	0.02
Cultivated land	14	650	9.1	1
Wetland	2	3000	6.0	15
Lake and stream	2	400	0.8	0.02
Total continent	**149**		**117.5**	
Open ocean	332	125	61.5	0.003
Upwelling	.4	500	0.2	0.02
Continental shelf	26.6	360	9.6	0.001
Reefs and algal beds	.6	2500	1.6	2
Estuaries	1.4	1500	2.1	1
Total Marine	361		75	
Total	510		193	

Redox Potential, Potential Energy, and Chemical Transformations

The relative availability (concentration) of electrons for chemical reactions in solution is referred to as **oxidation-reduction potential** or **redox potential**. This parameter is important because it quantifies potential energy requirements or yields during biotic or abiotic processes that transform chemical compounds in the environment. Even though the concept of redox can be difficult to grasp, it is worth the effort because it provides an understanding of the way that nutrients cycle in the environment. Building a rational framework based on principles of chemistry is essential to learn the cycles that underlie ecosystem function.

Redox potential of natural systems is simple to measure with electrodes that assess availability of transferable electrons relative to the availability of electrons in hydrogen gas. Such sensors read in millivolts, with negative values (e.g., below 100 mV) denoting large numbers of transferable electrons and high values of redox denoting transferable electrons. Even though redox potential is easy to measure, prediction of a single redox potential for natural aquatic habitat is difficult because of the myriad of chemical compounds that co-occur, and because the different compounds may not be at equilibrium. Some elements common in the earth's crust combine to form different organic and inorganic compounds that have a different affinity for electrons from each other. Although these elements should transfer electrons until they all have the same redox potential, in reality, some electron transfers are blocked leading to redox potentials that may vary for different elements.

The central idea that links the concept of redox potential to biogeochemical cycling is that chemical compounds have **potential energy** when they have a redox significantly different from their surrounding environment. Gibbs free energy diagrams are the best way to visualize the potential energy (Fig. 11.5). The redox potential of different chemical transformations can be plotted relative to each other (e.g., Fig. 11.6). The energy yield of a chemical transformation is the distance between the head and tail of the arrow. The transformation will yield potential energy if the redox potential of the solution is less than the head of the arrow for the reductions and greater than the head of the arrow for the oxidations.

It is important to distinguish the total potential energy to be gained or lost during conversion among chemical forms, in addition to determining the energy required for the reaction to occur. The energy required to make the conversion is called the activation energy (Fig. 11.5). The reaction will not occur rapidly if the activation energy needed is high. For example, ammonium can exist in an oxidized solution without spontaneously converting to nitrate, even though ammonium has a significantly higher potential energy than nitrate under oxidizing conditions. The activation energy of this conversion is too high for the reaction to proceed at significant rates under normal conditions found in natural aquatic environments.

Dissolved oxygen gas (O_2) is a major determinant of redox. This is because O_2 has a tremendous affinity for electrons. When O_2 is present, redox values are high, generally in excess of 200 mV. This high redox potential signals an oxidizing environment that allows only specific chemical reactions to proceed without a net input of energy.

Iron concentrations in a dimictic lake are an example of how O_2 concentrations regulate redox potential to control the concentration of a chemical in the aquatic environment (Fig. 11.7). In this case, ferrous iron (Fe^{2+}), the reduced form of iron, is soluble, but ferric iron (Fe^{3+}), the oxidized form of iron, forms an insoluble precipitate in water. Ferris iron converts readily to ferric iron in the presence of O_2 (i.e. the activation energy for the reaction is low) and then forms insoluble precipitates that settle with other sediments. When the lake is mixed fully and in contact with the atmosphere, iron concentrations are low throughout the water column. As O_2 is depleted from the deeper stratified layers, the dissolved iron concentration increases as ferrous iron diffuses out of the sediment. In this case, low redox potential and high dissolved iron concentrations are correlated closely.

Organisms can promote chemical reactions that would not otherwise occur by lowering the activation energy. This promotion is accomplished with enzymes that lower activation energy and catalyze the reactions. In the example above, where ammonium is stable in aquatic habitats containing O_2, microorganisms can lower the activation energy required to oxidize ammonium to nitrate. This reaction releases energy because nitrate has a lower potential energy than ammonium in the presence of O_2. The bacteria can direct this energy toward cellular growth. The process is called nitrification and will be discussed in greater detail in Chapter 13.

Organisms also can drive chemical reactions against potential energy (create more energetic chemical compounds). Such reactions require more input of potential energy than is stored in the products. Photosynthesis is an excellent example of a reaction that goes against potential energy; CO_2 is transformed to sugar (with a higher potential energy) using the energy of sunlight to accomplish the energy-requiring transformation.

Table 12.1. Some representative fermentative, methanogenic, and acetogenic transformations that occur in anoxic communities. Acetogenic and methanogenic processes require very low redox (Fig. 11.6). The listed processes represent a small proportion of the fermentative processes that can occur in anoxic communities.

Reaction	Name	Comment
Fermentation		
Glucose $\rightarrow$ 2 ethanol + 2 CO_2	Ethanol fermentation	Formation of alcohol
Glucose $\rightarrow$ 2 lactate + 2 H^+	Lactate fermentation	
Glucose $\rightarrow$ ethanol + acetate + CO_2 + H_2	Mixed acid fermentation	Produces variable amounts of products
Glucose $\rightarrow$ butyrate + 2 CO_2 + 2 H_2	Butyrate fermentation	
3 lactate $\rightarrow$ 2 Propionate + acetate + CO_2	Propionate fermentation	Gives Swiss cheese flavor
Alanine + 2 glycine $\rightarrow$ 3 acetate + 3 NH_3 + CO_2	Paired amino acid fermentation	Important when proteins being broken down
Acetogenesis		
2 CO_2 + 8 H^+ $\rightarrow$ acetate + 2 H_2O	Heterotrophic acetogenesis	
2 CO_2 + 4 H_2 $\rightarrow$ acetate + 2 H_2O	Autotrophic acetogenesis	
Methanogenesis		
CO_2 + 4 H_2 $\rightarrow$ CH_4 + 2 H_2O	Autotrophic methanogenesis	Uses CO_2 and H_2 as a source of energy
Acetate $\rightarrow$ CH_4 + CO_2	Acetoclastic methanogenesis	Disproportionation of acetate

The sequence of reactions from glucose to methane, modified from Conrad, 1999, FEMS Microbial Ecology 28:193-202

1. Fermentation	$C_6H_{12}O_6$ -> 3 CH_3COOH
2. Syntrophy	$C_6H_{12}O_6$ + 2 H_2O -> 2 CH_3COOH + 2 CO_2 +4 H_2
3. Hydrogenotrophic methanogenesis	4 H_2 + CO_2 -> 2 H_2O + CH_4
	$C_6H_{12}O_6$ + -> 2 CH_3COOH + 2 CO_2+ CH_4
4. Acetotrophic methanogenesis	CH_3COOH + 2 CO_2+ CH_4
	$C_6H_{12}O_6$ -> 3 CO_2+ 3CH_4

Table 22.4. Ecosystem function in some wetland types (after Mitsch and Gosselink 1993). See Table 4.4 for description of wetland types.

Type	Distribution	Production ($g\ C\ m^{-2}\ y^{-1}$)	Methane production ($mg\ C\ m^{-2}\ d^{-1}$)	Nutrient retention
Freshwater marsh	Worldwide	1000-6000	45-285	Sometimes N and P sink
Tidal freshwater marsh	Mid to high latitude, in regions with a broad coastal plain	1000-3000	440	N and P sink
Riparian wetland	Worldwide	600-1300	?	Sometimes N and P sink
Northern wetland	Cold temperate climates of high humidity, generally in Northern Hemisphere	240-1500	0.1 – 90	Usually N and P sink, may be an N source
Deepwater swamp	Southeast United States	200-1700	1-15	

Table 13.1. Some sulfur transformations. Note: others occur, but this table partially illustrates the complexity of the sulfur cycle.

Equation	Conditions	Name	Classification
$H_2S + \frac{1}{2} O_2 \rightarrow S^o + H_2O$	Oxic	Sulfide oxidation	Abiotic and dissimilatory biotic
$S^o + H_2O + 1\frac{1}{2} O_2 \rightarrow H_2SO_4$	Oxic	Elemental sulfur oxidation	Abiotic and dissimilatory biotic
$4NO_3^- + 3S^o \rightarrow 3SO_4^{2-} + 2N_2$	Anoxic	Inorganic sulfur oxidation	Dissimilatory biotic
$2CO_2 + 2H_2S + 2H2O + \text{light} \rightarrow 2(CH_2O) + H_2SO_4$	Anoxic	Photosynthetic sulfur oxidation (anoxygenic photosynthesis)	Biotic
$CH_3COOH + 2H_2O + 4S^o \rightarrow 2CO_2 + 4H_2S$	Anoxic	Acetate oxidation	Dissimilatory, reduction
$2(CH_2O) + H_2SO_4 \rightarrow 2CO_2 + 2H_2O + H_2S$	Anoxic	Anaerobic respiration, sulfate as the electron acceptor	Dissimilatory, reduction
$4 H_2 + H_2SO_4 \rightarrow 4H_2O + H_2S$	Anoxic	Anaerobic hydrogen respiration	Dissimilatory, reduction
$S_2O_3 \rightarrow SO_4^{2-} + S^{2-} + H^+$	Anoxic	Disproportionation	Dissimilatory
$SO_4^{2-} \rightarrow S^{2-} \rightarrow$ cysteine	Oxic/ anoxic	Assimilation	Biotic
$H_2S + Fe^{2+} \rightarrow FeS + H_2$	Anoxic	Iron pyrite formation	Abiotic, spontaneous

Table 16.2. Elemental composition of algae and plants compared to availability in freshwater (world rivers). All composition data are in moles or atoms relative to molybdenum. Data on algae from Healy and Stewart (1973) and on plants and algae and rivers from Vallentyne (1974). Average demand/supply is algae and plants divided by rivers.

Element	Plants and Algae	World Rivers	Average Demand/Supply
H	13,400,000	3,520,000,000	<<1
O	5,880,000	1,780,000,000	<<1
C	2,750,000	31,900	86
N	689,000	525	1312
Si	163,000	7,390	22
K	34,900	1,880	18
P	24,400	10	2440
Ca	23,300	12,000	2
Na	17,900	8,340	2
Mg	17,100	5,260	3
S	13,700	3,980	3
Fe	7,240	401	18
Zn	314	5	63
B	264	296	1
Cu	102	5	20
Mn	82	9	9
Mo	1	1	1

Table 16.3. Size fractionation of regeneration of ammonium and phosphate in the epilimnion of pelagic freshwater systems. The % categories are the % regeneration in the size fraction above the high cutoff (% high), between high and low (% medium) and below low (% small). Where several seasons were studied, ranges are presented for the percentages.

Lake	Nutrient	High cutoff (µm)	Low cutoff (µm)	% high	% medium	% small	Reference
Lake Calado (Amazon floodplain)	N	20	3	1	39	60	Fisher et al. (1988)
Lake Calado (Amazon floodplain)	P	20	3	0	0-45	55-100	Fisher et al. (1988)
Flathead Lake (Montana)	N	280	3	0-10	10-25	75-100	Dodds et al. (1991)
Flathead Lake (Montana)	P	280	3	0-30	0-45	50-100	Dodds et al. (1991)
Lake Biwa (Japan)	N	98	-	50	-	50	Urabe et al. (1995)
Lake Biwa (Japan)	P	98	-	15	-	85	Urabe et al. (1995)
Lake Biwa (Japan)	N	100	20	3-16	7-18	63-98	Haga et al. (1995)
Lake Kizaki (Japan)	N	100	20	1-62	27-68	40-70	Haga et al. (1995)
Ranger Lake (Ontario)	P	40	0.8	52	30	18	Hudson and Taylor (1996)
Mouse Lake (Ontario)	P	40	0.8	15	65	20	Hudson and Taylor (1996)
Lake Herrensee (Germany)	P	150	-	18	-	82	Hantke et al. (1996)
Lake Bräuhaussee (Germany)	P	150	-	11	-	89	Hantke et al. (1996)
Lake Thaler See (Germany)	P	150	-	2	-	98	Hantke et al. (1996)

	Size	biomass (kg/ha)	turnover/y	generation time (H)
amoebae	30 µm	45	10	3
flagellates	10 µm	4	10	3
cilliates	80 µm	1	10	3
bacteria	.5-02 µm	600	2	0.5
fungi	1-5 µm	1500	0.75	5
Mites	50 µm	2	2	120
Collembola	1 mm	0.3	2	720
mites	1 mm	5	2	720
Enchytraeids	1 mm	4		170
Earthworms	100mm	30	3	720

Coleman 1994 Microb. ecol. 28:245-250

Estimates of microzooplankton grazing on phytoplankton (grazers < 200 µm) from Sherr and Sherr 1994. Microb. Ecol. 28:223-235

Location	% primary production grazed per day
Washington coast	17-52
Celtic Sea	13-65
Arctic Jones Sound	40-114
Arctic Baffin Bay	37-88
Halifax Harbour	47-100
Rhode River Estuary	45-104
Grand Bank Newfoundland	50-70
Subarctic Pacific	40-60
Equatorial Pacific	44-90
Northeast Atlantic	39-115
Indian Ocean	70-100
Oregon Upwelling	26-50

Protozoan concentration and species in water buffalo and cattle (from The Rumen Microbial Ecosystem)

Host and location	# animals	total protozoa 10000/mL	# species
Water buffalo			
Indonesia	17	0.1-32	8-20
Thailand	10	0.2-2	2-17
Taiwan	29	0.5-316	3-25
Philippines	2	1.5-8	7-9
Brazil	4	17-36	22-35
Okinawa	5	27-50	10
Zebu Cattle			
Thailand	46	1-32	14-39
Philippines	4	13-18	18-22
Senegal	24	4-31	8-18
Sri Lanka	20	.1-32	6-29
Brazil	4	9-51	22-36
Cattle			
Japan	69	0.5-3981	4-25

Animals with nutritionally mutualistic microbes

Animal	Microbe	Location
Wood roach	Flagellate protozoa	Post-Peptic
termites	Flagellates, bacteria, or fungi	Post-Peptic and cultivated fungi
grouse and ptarmigan	Bacteria	Post-Peptic
marsupials	Ciliate protozoa and bacteria	Pre-Peptic
colbid and langur monkeys	Bacteria	Pre-Peptic
Sloths	Bacteria	Pre-Peptic
Rodents	Bacteria	Post-Peptic and coprophagy
Rabit and Hare	Bacteria	Post-Peptic and coprophagy
Elephant and Hyrax	Bacteria and ciliates	Post-Peptic
Hippopotamus and peccary	Bacteria and ciliates	Pre-Peptic
Dugong and Manatee	Bacteria	Post-Peptic
Camel, llama and alpaca	Bacteria and ciliates	Post-Peptic
Horse, zebra, tapir, and rhinoceros	Bacteria and ciliates	Post-Peptic
Domestic ruminants	Bacteria, fungi, and ciliates	Pre-Peptic

Table 15.1. Upper salinity tolerances of some members of selected groups of organisms (data from Javor 1989).

Organism	Upper salinity range (%)
Fish	11
Nematodes	12.5
Ostracods	13
Gastropods	15.9
Rotifers	16
Isopods	16
Copepods	17.6
Diatoms	20.5
Chironomids	28.5
Ephydra cinerea	30
Anostracans (*Artemia salina*, brine shrimp)	33
Cyanobacteria	35
Ciliate protozoa	35
Green algae (*Dunaliella*)	35
Anostrocans (*Parartemia salina*)	35.3
Phototrophic bacteria	40
Extreme halophilic bacteria	Saturated

Table 15.2. Upper temperature tolerances for various groups of organisms (from Brock 1978).

Group	Approximate upper limit (^{o}C)
Fish	38
Vascular plants	45
Insects	50
Ostracods	50
Mosses	50
Protozoa	56
Algae (eukaryotic)	60
Fungi	62
Cyanobacteria	73
Photosynthetic bacteria	73
Extreme thermophilic Bacteria and Archaea	110?

Spread of plasmids encoding strepothricin resistance in various bacterial populations in Germany (Tscahpe 1994. FEMS Microbiol Ecol. 15:23-32.). dash means no check was made.

Origin	1982 (application)	1983	1984	1985	1986	1987	1989-1993 after application
gut flora of pigs	-	I2, W3	I2, W3, X	-	-	-	I2, W3, X
pig manure	-	I2, W3	I2, W3, X	-	-	-	I2, W3, X
personel gut flora	-	-	I2, X	X, W3	-	-	I2, W3, X
personel family gut flora	-	-	-	-	-	-	I2, W3, X
urban population gut flora	-	-	-	X, W3, I2	-	-	I2, W3, X
food	-	-	-	X, I2	I2, W3, X	-	I2, W3, X
sick animals	-	-	-	I2, W3, X	-	-	I2, W3, X
urinary infections	-	-	-	-	X	-	X
salmonellosis	-	-	-	-	I2, X	-	I2
shigellosis	-	-	-	-		X	none