
Biographical Sketch

The author is a Professor in the School of Biology and Ecology at the University of Maine, Orono, ME. He wrote a previous introductory textbook entitled *Introduction to Ecology and Ecosystems Analysis*, and has published over 70 peer-reviewed scientific articles in journals such as *Bioscience*, *Science*, *Nature*, *Water Resources Research*, *Environmental Science and Technology*, *Ecological Modeling*, *Landscape Ecology*, *Tree Physiology*, *Biogeochemistry*, *Analytical Chemistry*,

Soil Science Society of America Journal, *Geochimica Cosmochimica Acta*, and *Environmental Management*. He is former director of the School of Biology and Ecology and founding director of the Graduate Program in Ecology and Environmental Science at the University of Maine. The author earned a B.A. in Ecology at the University of Pennsylvania and a Ph.D. in Biological Sciences at Dartmouth College.

Epilogue

Biogeochemical processes are part of an amazing *complex adaptive system* in the biosphere that is characterized by diverse interconnections and feedbacks, coupled with remarkable emergent patterns and properties expressed in the form of biological and ecological diversity, ecosystem services, and human creativity and culture. At present, the biosphere and its inhabitants represent a system in transition. We are in a time of dynamic changes and adjustments in the world economy, in the social fabric of human cultures, and in the interconnected life systems of the biosphere. Arctic summer sea ice expanse has reached another historic minimum, greenhouse gas emissions from human activities are ever increasing, biodiversity is at risk from multiple stresses, water tables are declining in many regions, and the evidence of biogeochemical imbalances and disturbances is apparent across the globe. In a human population that has grown to over 7 billion persons, we have the seeds of a future teetering on the edge of disaster, famine, and stress, but we also have a rising wave of incredible human creative energy and intellectual capital. Both fear and hope seem to be in constant struggle in the minds and lives of many.

So, what are the options? Is it reasonable to think that human knowledge, ingenuity, compassion, and cooperation can provide a means of confronting and overcoming these global challenges? Certainly, it is reasonable, but is it likely? Perhaps one meaningful way to answer this question is to say that solutions to these challenges will be more likely to arise if we can forge a shared vision based on sustainable principles and actions. The challenge then becomes one of defining a working approach by which human society makes more efficient use of resources, reduces consumption, minimizes the human footprint of development and waste generation, and embraces a sea change in the current rules of the marketplace.

By some means, we must articulate and implement a vision of stewardship, human development, and global commerce that measures up to the standards of sustainability. This is the global challenge we face – to transform knowledge into wisdom and wisdom into sustainable decisions and actions that support and maintain the creative potential and health of human civilization and the entire biosphere.

Problem Sets

Sample Problems in General Chemistry

1. A rock sample contains 15% Al_2O_3 by weight. What is the concentration of Al in mg kg^{-1} ?
2. A leaf contains 2.0% nitrogen on a dry weight basis. What is the N concentration in ppm (parts per million)? If the fresh leaf contains 75% water, what is the N concentration on a fresh weight or wet weight basis?
3. How do you prepare a 5×10^{-3} M solution of phosphate using KH_2PO_4 ?
4. What is the H^+ ion activity in moles L^{-1} of a water sample at pH 4.73?
5. What is the pH of a water sample containing 0.000165 moles $\text{H}^+ \text{L}^{-1}$?
6. What mass of NaOH would be required to neutralize 3000 L of pH 4.5 rainwater?
7. The isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr}$ for an ocean water standard is 0.70923
 - (a) If the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for atmospheric aerosols in New York is 0.70931, what is the delta value ($\delta^{87}\text{Sr}$) of this sample *permil* relative to the ocean standard?
 - (b) If the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for feldspar minerals in New York is 0.70516, what is the delta value ($\delta^{87}\text{Sr}$) of this sample *permil* relative to the ocean standard?
8. Rain begins to fall from an air mass whose initial $\delta^{18}\text{O}$ value is -9.0‰ ; the fractionation factor ($\alpha_{\text{liquid-vapor}}$) is 1.0092 at the condensation temperature.
 - (a) Apply the Raleigh Distillation Equation to compute the isotopic composition of the air mass after 60% of the water vapor has recondensed. Express your answer as $\delta^{18}\text{O}$.
 - (b) Compute the isotopic composition of the resulting rainwater as a value of $\delta^{18}\text{O}$.

Sample Problems in Soil Chemistry

9. You have a mineral soil with a moisture content of 50% and a bulk density of 1.5 g cm^{-3} . You want to determine the concentrations of exchangeable cations and the percent base saturation. You extract 5.0 g of field-moist soil

with 100 ml of 1 M NH_4Cl and a separate 5.0 g of soil with 100 ml of 2 M KCl. You centrifuge and filter the supernatants of each soil extraction and use an AAS instrument to estimate the following concentrations of cations in each supernatant:

Cation	Concentration in Extract, mg L^{-1}
H^+	0.25
Al^{3+}	22.5
Ca^{2+}	5.0
Mg^{2+}	0.30
K^+	0.78
Na^+	0.06

- (a) What are the exchangeable cation concentrations in $\text{cmol}(+) \text{ kg}^{-1}$?
 - (b) What is the effective cation exchange capacity (CEC)? [Effective CEC = sum of all exchangeable cations at field pH]
 - (c) What is the percent base saturation (% B.S.) for the soil?
 - (d) What is the pool of exchangeable Ca in the uppermost 20 cm of this soil (expressed in moles $(+) \text{ ha}^{-1}$)?
10. For the soil in the previous problem, it is known from laboratory titration that this soil has a pH of 4.5 at 10% base saturation and a pH of 5.5 at 40% base saturation. How much limestone (CaCO_3) would theoretically be required to increase the base saturation from 10% to 40% in the uppermost 20 cm of soil?

Sample Problems in Atmospheric Deposition

11. The precipitation sample shown below was collected on a mountain in New England and was rushed to the laboratory for immediate analysis. How would the chemistry and pH change if nitrification by microbial contaminants occurred in the water sample prior to analysis and all of the NH_4^+ was nitrified? The ion concentrations are expressed in $\mu\text{mol L}^{-1}$. Indicate final pH and concentrations of ammonium and nitrate.

	H ₂ O (cm)	pH	Ca	Mg	NH ₄ ⁺	SO ₄ ²⁻	NO ₃ ⁻
Rain Sample	2	4.10	11	5	22	98	25

12. Listed below are data for monthly mean precipitation amounts and sulfate ion concentrations at one location in the southeastern United States.

Month	Precipitation (cm)	Sulfate (mg L ⁻¹)
1	31.8	3.5
2	18.7	3.9
3	38.7	3.4
4	23.4	3.8
5	19.5	2.9
6	5.1	3.2
7	2.9	3.0
8	2.1	2.4
9	4.6	2.6
10	1.8	3.2
11	9.8	2.7
12	20.4	3.0

- Compare the unweighted and volume-weighted annual mean sulfate concentrations.
- Calculate the annual wet deposition of sulfate (SO₄²⁻) in mol_c ha⁻¹ yr⁻¹ and sulfate-S in kg S ha⁻¹ yr⁻¹.
- If the mean annual volume-weighted pH of precipitation is 4.3 at this site, what is the approximate annual H⁺ ion deposition in mol_c ha⁻¹ yr⁻¹?

Sample Problem in Hydrology

13. Visit the Water Resources of Maine website at <http://me.water.usgs.gov> and use the data base to survey hydrologic runoff records for the Aroostook River at Masardis (site number 01015800). You can use this USGS data base to find all kinds of historical and real-time data for streamflow conditions. I have previously asked students to find specific peak flow records in the online data base, but the USGS keeps changing the site and updating the runoff numbers, which means that the problem answer keeps changing to match changes in the data base. As a result, I am providing the runoff value below that is required to answer the problem.
- During the period 1978–1998, the highest daily runoff flow occurred on 4/19/83 and reached a value of 23,100 cfs. For this watershed, the drainage area is 892 square miles. Express that peak flow in the following two different units: cubic meters per second (m³/s), and cm of flow per day from the drainage basin. The last term expresses peak flow on a unit area basis similar to the measurement of precipitation inputs (e.g., so many cm of rainfall per 24-h day).
 - Retrieve the daily mean discharge data for the same river site during the period September 1, 1999 to

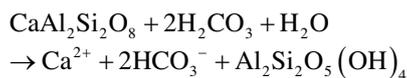
September 30, 1999. Prepare a flow duration or exceedence graph for the September data using a log scale on the y-axis labeled Daily Runoff (cfs) and an arithmetic scale on the x-axis labeled Frequency of Runoff this High.

Sample Problems in Mineral Weathering

14. You have been hired to analyze data from a U.S. Forest Service watershed to determine the relative contributions of atmospheric deposition and weathering to stream cation exports. A previous vegetation study indicated that net annual biomass increment in the watershed is 1000 kg dry matter ha⁻¹ yr⁻¹ with mean weighted cation concentrations for the biomass increment of 0.5% Ca, 0.5% Mg, and 1.0% K (with no detectable Na). The hydrologic budget shows 100 cm of precipitation, 40 cm of evapotranspiration, and 60 cm of stream runoff. Estimate weathering in mol_c ha⁻¹ yr⁻¹ for each of the four major cations; show your work and state your assumptions.

	Ca	Mg	K	Na
Precipitation Chemistry				
Weighted mean, mg L ⁻¹	0.20	0.06	0.20	0.12
Stream Chemistry				
Weighted mean, mg L ⁻¹	2.00	0.30	0.78	1.15

- Most experimental studies of weathering indicate that dissolution of feldspars increases as a function of solution acidity. Which solution would produce a faster initial rate of weathering: a solution of an organic acid such as fulvic acid at pH 4.85 or an aqueous solution of carbonic acid in equilibrium with a pCO₂ of 1.5%? Show your work and explain your answer.
- How much acid neutralizing capacity (ANC) is released during the weathering of 15.0 g of anorthite, a calcium feldspar (as illustrated below)? Show your computational steps, your ANC expression, and present your answer in mmol_c.



Sample Problems in Element Cycling and Aqueous Chemistry

17. A forest calcium budget shows an annual Ca uptake by plants of 56 kg ha⁻¹. Focusing only on Ca and assuming that Ca²⁺ uptake is coupled with proton release from the plant root to the soil rhizosphere, what is the potential

H⁺ ion release associated with the annual uptake of Ca? Show your work and express your answer in mol_c ha⁻¹ yr⁻¹. How does this estimate compare with the average annual atmospheric wet deposition of H⁺ ion in New England (assuming mean pH = 4.3 and annual precipitation = 100 cm)?

18. Consider a watershed where the weighted annual mean concentration of chloride ion in precipitation is 25 μmol(-) L⁻¹, the average annual stream runoff is 65% of precipitation inputs, and water storage is stable (i.e., steady-state on an annual basis). If you assume that chloride moves “conservatively” through the system without enrichment or depletion of mass (from uptake, mineralization, adsorption, or weathering), what is the final weighted annual mean concentration of Cl⁻ ion in stream water?
19. Consider a forest with an annual N uptake of 50 kg N ha⁻¹ yr⁻¹, rainfall equivalent to 100 cm, and transpiration equivalent to 25% of rainfall. If we assumed that the forest acquires all of its N via passive bulk flow of transpirational water, what concentration of N in the soil water (as dissolved inorganic N) is necessary to allow the forest to take up 50 kg N ha⁻¹ yr⁻¹? Express your answer as the solution concentration of inorganic N in mg L⁻¹. [Note that concentrations of inorganic N in field soil solutions are commonly <10% of the mean value you have calculated; this suggests that plants must use energy-dependent active uptake to meet their N demand].

Sample Problems in Organic Matter Cycling

20. Data are presented below indicating the chemical composition of fresh leaf litter from three **northern tree species**. Use the data to predict which litter substrate would decay fastest. Rank the species from highest to lowest in order of their expected rates of decay. Show your logic or computations, and indicate the literature reference(s) upon which your rationale is based.

Species	%N	%Ca	%K	%Lignin
A	1.6	0.05	0.12	12.0
B	1.6	0.07	0.18	16.0
C	2.4	0.10	0.22	18.0

21. What is the estimated annual CO₂ release from microbial decomposition of organic matter in the forest floor (O horizon) of an ecosystem under the following conditions? State any assumptions and express CO₂ release in g CO₂ m⁻² yr⁻¹
 - The forest floor is assumed to be in steady-state
 - Forest floor mass is 50,000 kg organic matter ha⁻¹

- Annual inputs of detritus to the forest floor from litterfall + root mortality
+ throughfall DOM = 2500 kg organic matter ha⁻¹ yr⁻¹
22. Does leaf decay generate acidity or alkalinity? Consider a gram of decaying leaf with the composition shown below. Estimate the net ANC production that will likely result from complete microbial mineralization of this leaf with an initial mass of 1.0 g. Show three possible outcomes for this decomposition process based on the following assumptions: (1) assume that all of the N is only subject to ammonification, (2) assume that all of the N is subject to ammonification followed by 100% nitrification, and (3) assume all of the mineralized N is ultimately denitrified to dinitrogen, N₂. Remember to consider the other elements as well.

Foliar concentrations (shown below) in parts per thousand in a leaf weighing 1.0 g

Carbon = 480	Nitrogen = 7	Sulfur = 2
Calcium = 8	Potassium = 4	Magnesium = 1

Sample Problems on Element Budgets

23. Use the data below to estimate how much calcium is exported from this watershed in a 1-year time period. Express your answer in moles of charge (mol_c yr⁻¹) and indicate any assumptions you made. (note that cfs = cubic feet per second)

Month	Mean daily flow (cfs)	Mean Daily Ca concentration mg L ⁻¹
J	1000	3
F	1500	3
M	1200	3
A	4000	2
M	6000	2
J	3000	3
J	500	5
A	500	6
S	2000	3
O	4000	3
N	7000	2
D	1000	2

24. Consider a forest soil where the subsurface pool of soil organic matter contains 150,000 kg C ha⁻¹ and decays at an annual rate of 0.5% yr⁻¹. What is the mean residence time of this carbon pool and how much carbon as root detritus and DOM must be transferred into this pool each year (in units of g C m⁻² yr⁻¹) to maintain it at steady-state? How does this estimate compare with reported values of fine root biomass and turnover?

Problem Answers

Sample Problems in General Chemistry

1. A rock sample contains 15% Al_2O_3 by weight. What is the concentration of Al in mg kg^{-1} ?

Answer:

Formula Weight of $\text{Al}_2\text{O}_3 = (2 \times 27) + (3 \times 16) = 102 \text{ g}$
Aluminum represents 54/102 or 52.9% of the formula weight

The rock sample contains 15 g Al_2O_3 per 100 g of total rock
The aluminum content equals 52.9% of the Al_2O_3 or
 $0.529 \times 15 \text{ g Al}_2\text{O}_3 = 7.935 \text{ g}$

Thus, the rock contains 7.935 g Al per 100 g rock
Multiply numerator and denominator by 10 to scale up to a kg

This gives 79.35 g Al per 1000 g rock

Multiply the numerator by 1000 mg per g to get (79.35 g Al/ kg rock) $\times (1000 \text{ mg/g})$

This yields 79,350 mg Al kg^{-1} rock

2. A leaf contains 2.0% nitrogen on a dry weight basis. What is the N concentration in ppm (parts per million)? If the fresh leaf contains 75% water, what is the N concentration on a fresh weight or wet weight basis?

Answer:

2% N = 2 mg N per 100 mg dry leaf

1 ppm = 1 mg per 1000,000 mg, so we must multiply by 10,000 to get the nitrogen mass associated with one million mg of dry leaf material

Multiply (2 mg N / 100 mg dry leaf) $\times 10^4/10^4 = 20,000 \text{ mg N} / 1000,000 \text{ mg dry leaf}$

This is equivalent to 20,000 ppm N

On a fresh weight basis with 75% water, you have 1 part dry mass per 4 parts total mass

$20,000 \text{ ppm N} \times (1 \text{ part dry mass} / 4 \text{ parts dry mass} + \text{water}) = 5000 \text{ ppm N}$

3. How do you prepare a $5 \times 10^{-3} \text{ M}$ solution of phosphate using KH_2PO_4 ?

Answer:

The formula weight for this compound is $39 + 2 + 31 + 64 = 136 \text{ g}$

The final concentration is 0.005 M

$0.005 \text{ M} \times 136 \text{ g / mole} = 0.68 \text{ g KH}_2\text{PO}_4$

4. What is the H^+ ion activity in moles L^{-1} of a water sample at pH 4.73?

Answer:

Since pH is the negative log of hydrogen ion activity, to compute molar H^+ ion activity from pH, take the value of $10^{-\text{pH}}$ or $10^{-4.73}$, which equals $1.86 \times 10^{-5} \text{ M L}^{-1}$

5. What is the pH of a water sample containing 0.000165 moles $\text{H}^+ \text{ L}^{-1}$?

Answer:

$$\text{pH} = -\log(0.000165) = 3.78$$

6. What mass of NaOH would be required to neutralize 3000 L of pH 4.5 rainwater?

Answer:

Rainwater acidity = $10^{-\text{pH}} = 10^{-4.5} = 0.0000316 \text{ moles H}^+ \text{ L}^{-1}$

$3000 \text{ L} \times 0.0000316 \text{ moles H}^+ \text{ L}^{-1} = 0.0948 \text{ moles H}^+$

This must be balanced by an equivalent amount of NaOH (formula weight = 40 g)

$0.0948 \text{ mole NaOH} \times 40 \text{ g / mole NaOH} = 3.79 \text{ g NaOH}$ to neutralize acidity

7. The isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr}$ for an ocean water standard is 0.70923

(a) If the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for atmospheric aerosols in New York is 0.70931, what is the delta value ($\delta^{87}\text{Sr}$) of this sample *permil* relative to the ocean standard?

Answer:

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) * 1000$$
$$= \left[\frac{(0.70931 - 0.70923)}{0.70923} \right] * 1000 = +0.1128\text{‰}$$

- (b) If the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for feldspar minerals in New York is 0.70516, what is the delta value ($\delta^{87}\text{Sr}$) of this sample *permil* relative to the ocean standard?

Answer:

$$\left[(0.70516 - 0.70923) / 0.70923 \right] \times 1000 = -5.7386\text{‰}$$

8. Rain begins to fall from an air mass whose initial $\delta^{18}\text{O}$ value is -9.0‰ ; the fractionation factor ($\alpha_{\text{liquid-vapor}}$) is 1.0092 at the condensation temperature.

- (a) Apply the Raleigh Distillation Equation to compute the isotopic composition of the air mass after 60% of the water vapor has recondensed. Express your answer as $\delta^{18}\text{O}$.

Answer:

$$\begin{aligned} \delta^{18}\text{O}_{\text{air mass}} &= \left[(\delta^{18}\text{O}_o) + 1000 \right] f^{(\alpha-1)} - 1000 \\ &= \left[(-9.0\text{‰}) + 1000 \right] \times (0.4)^{(1.0092-1)} - 1000 \\ &= -8.92445 + 991.60556 - 1000 \\ &= -17.32\text{‰} \end{aligned}$$

- (b) Compute the isotopic composition of the resulting rain-water as a value of $\delta^{18}\text{O}$.

Answer:

$$\begin{aligned} \delta^{18}\text{O}_{\text{rainwater}} &= \alpha (\delta^{18}\text{O}_{\text{vapor}} + 1000) - 1000 \\ &= 1.0092 (-17.32\text{‰} + 1000) - 1000 \\ &= -17.48\text{‰} + 1009.2 - 1000 \\ &= -8.28\text{‰} \end{aligned}$$

Sample Problems in Soil Chemistry

9. You have a mineral soil with a moisture content of 50% and a bulk density of 1.5 g cm^{-3} . You want to determine the concentrations of exchangeable cations and the percent base saturation. You extract 5.0 g of field-moist soil with 100 ml of 1 M NH_4Cl and a separate 5.0 g of soil with 100 ml of 2 M KCl . You centrifuge and filter the supernatants of each soil extraction and use an AAS instrument to estimate the following concentrations of cations in each supernatant:

Cation	Concentration in Extract, mg L^{-1}
H^+	0.25
Al^{3+}	22.5
Ca^{2+}	5.0
Mg^{2+}	0.30
K^+	0.78
Na^+	0.06

- (a) What are the exchangeable cation concentrations in $\text{cmol}(+) \text{ kg}^{-1}$?

Answer:

The general principle is that you must convert extract concentrations to centimoles of ionic charge and then transform this value to cmol_c per kg of dry soil. If a mol_c of Al^{3+} has a mass of 9.0 g (based on a formula weight of 27 g / valence of 3+), then a cmol_c of Al^{3+} has 1/100th of that mass or 0.09 g or 90 mg. In the example above, you extract 5.0 g of moist soil that has 50% moisture content, so you actually have 2.5 g dry soil. You are extracting the soil in 100 ml of salt solution, which is one-tenth of a liter. This means that the absolute value of extracted cation in the 100 ml volume is 10% of the extract concentration listed above in mg L^{-1} .

Let's look at an example for Ca^{2+} from the list of extracted cations.

Convert the supernatant extract concentration to $\text{cmol}_c \text{ L}^{-1}$

$$5 \text{ mg Ca}^{2+} \text{ L}^{-1} \times 1 \text{ cmol}_c / 200 \text{ mg Ca}^{2+} = 0.025 \text{ cmol}_c \text{ Ca}^{2+} \text{ L}^{-1}$$

Scale the ion concentration in the 100 ml extract to a concentration per mass of dry soil

$$0.025 \text{ cmol}_c \text{ Ca}^{2+} \text{ L}^{-1} \times (0.1 \text{ L extract volume} / 2.5 \text{ g dry soil}) = 0.0025 \text{ cmol}_c / 2.5 \text{ g dry soil}$$

Then, scale to 1 kg dry soil

$$(0.0025 \text{ cmol}_c / 2.5 \text{ g dry soil}) \times (1000 \text{ g} / \text{kg}) = 1.0 \text{ cmol}_c \text{ Ca}^{2+} \text{ kg}^{-1} \text{ dry soil}$$

Using that approach, the exchangeable cation concentrations in $\text{cmol}(+) \text{ kg}^{-1}$ are as follows:

$$\begin{aligned} \text{H}^+ &= 1, \text{Al}^{3+} = 10.0, \text{Ca}^{2+} = 1.0, \text{Mg}^{2+} \\ &= 0.1, \text{K}^+ = 0.08, \text{and Na}^+ = 0.008. \end{aligned}$$

- (b) What is the effective cation exchange capacity (CEC)?

[Effective CEC = sum of all exchangeable cations at field pH]

Answer:

$$\begin{aligned} \text{Effective CEC} &= \text{sum of exchangeable } \text{H}^+ + \text{Al}^{3+} + \text{Ca}^{2+} \\ &+ \text{Mg}^{2+} + \text{K}^+ + \text{Na}^+ \\ &= 1 + 10 + 1 + 0.1 + 0.08 + 0.008 = 12.19 \text{ cmol}(+) \text{ kg}^{-1} \end{aligned}$$

- (c) What is the percent base saturation (% B.S.) for the soil?

Answer:

The percent base saturation equals the sum of base forming cations as a percentage of the CEC.

$$\begin{aligned} \% \text{B.S.} &= \left[\frac{(\text{Sum of Exchangeable Ca} + \text{Mg} + \text{K} + \text{Na})}{\text{CEC}} \right] \times 100 \\ &= (1.188 / 12.19) \times 100 = 9.74\% \end{aligned}$$

(d) What is the pool of exchangeable Ca in the uppermost 20 cm of this soil (expressed in moles (+) ha⁻¹)?

Answer:

The volume of soil per square meter = 20 cm depth × 10⁴ cm² m⁻² = 2 × 10⁵ cm³ m⁻²

Multiply by soil bulk density to get 1.5 g cm⁻³ × 2 × 10⁵ cm³ m⁻² = 3 × 10⁵ g m⁻²

Divide by 1000 to convert soil mass to kg basis = 300 kg soil m⁻²

Given a soil exchangeable concentration of 1.0 cmol_c Ca²⁺ kg⁻¹ dry soil, compute the following:

Exchangeable Ca²⁺ = 1.0 cmol_c Ca²⁺ kg⁻¹ × 300 kg soil m⁻² = 300 cmol_c Ca²⁺ m⁻²

Convert to moles: 300 cmol_c Ca²⁺ m⁻² × (1 mol_c Ca²⁺ / 100 cmol_c Ca²⁺) = 3 mol_c Ca²⁺ m⁻²

Scale to one hectare, where 1 ha = 10⁴ m²

3 mol_c Ca²⁺ m⁻² × 10⁴ m² ha⁻¹ = 30,000 moles(+) ha⁻¹

10. For the soil in the previous problem, it is known from laboratory titration that this soil has a pH of 4.5 at 10% base saturation and a pH of 5.5 at 40% base saturation. How much limestone (CaCO₃) would theoretically be required to increase the base saturation from 10% to 40% in the uppermost 20 cm of soil?

Answer:

From earlier steps, we know that CEC = 12.2 cmol_c kg⁻¹, exchangeable Ca²⁺ = 1.0 cmol_c kg⁻¹, and the exchangeable pool of Ca²⁺ in the upper 20 cm of soil = 30,000 mol_c ha⁻¹

Compute the CEC per hectare as follows:

(12.2 cmol_c CEC kg⁻¹ / 1.0 cmol_c Ca²⁺ kg⁻¹) × 30,000 mol_c Ca²⁺ ha⁻¹ = 366,000 mol_c CEC ha⁻¹

10% base saturation = 0.10 × 366,000 mol_c CEC ha⁻¹ = 36,600 mol_c ha⁻¹

40% base saturation = 0.40 × 366,000 mol_c CEC ha⁻¹ = 146,400 mol_c ha⁻¹

To increase the base saturation from 10% to 40% requires the addition of exchangeable bases equal to:

146,400 - 36,600 = 109,800 mol_c ha⁻¹

One mol_c of CaCO₃ = formula weight / valence of 2⁺ = 100 g / 2 = 50 g = 0.050 kg

(0.05 kg CaCO₃ / mol_c) × (109,800 mol_c / ha) = 5490 kg CaCO₃ per hectare

Sample Problems in Atmospheric Deposition

11. The precipitation sample shown below was collected on a mountain in New England and was rushed to the laboratory for immediate analysis. How would the chemistry and pH change if nitrification by microbial contaminants occurred in the water sample prior to analysis and all of the NH₄⁺ was nitrified? The ion concentrations are

expressed in μmol L⁻¹. Indicate final pH and concentrations of ammonium and nitrate.

	H ₂ O	pH	Ca	Mg	NH ₄ ⁺	SO ₄ ²⁻	NO ₃ ⁻
	(cm)						
Rain Sample	2	4.10	11	5	22	98	25

Answer:

Use a basic equation for nitrification as follows: NH₄⁺ + 2O₂ → NO₃⁻ + H₂O + 2H⁺

Substitute in the stoichiometric values shown above for the rain sample

22NH₄⁺ + 44O₂ → 22NO₃⁻ + 22H₂O + 44H⁺

Final NH₄⁺ = 0 μmol L⁻¹

Final NO₃⁻ = 25 + 22 = 47 μmol L⁻¹

Initial H⁺ = 10^{-4.1} = 0.000079 M L⁻¹ = 79 μmol L⁻¹

Final H⁺ = 79 + 44 = 123 μmol L⁻¹ = 0.000123 M L⁻¹

pH = -log [0.000123] = 3.91

12. Listed below are data for monthly mean precipitation amounts and sulfate ion concentrations at one location in the southeastern United States.

Month	Precipitation (cm)	Sulfate (mg L ⁻¹)
1	31.8	3.5
2	18.7	3.9
3	38.7	3.4
4	23.4	3.8
5	19.5	2.9
6	5.1	3.2
7	2.9	3.0
8	2.1	2.4
9	4.6	2.6
10	1.8	3.2
11	9.8	2.7
12	20.4	3.0

(a) Compare the unweighted and volume-weighted annual mean sulfate concentrations.

Answer:

The unweighted mean concentration is the sum of the 12 monthly sulfate values divided by 12.

= 3.13 mg SO₄²⁻ L⁻¹

The volume-weighted mean is calculated by weighting each monthly sulfate concentration by the monthly precipitation value in cm, using the following relationship:

Σ (concentration_i × cm of precipitation_i) / Σ cm of precipitation = 3.34 mg SO₄²⁻ L⁻¹

(b) Calculate the annual wet deposition of sulfate (SO₄²⁻) in mol_c ha⁻¹ yr⁻¹ and sulfate-S in kg S ha⁻¹ yr⁻¹.

Answer:

3.34 mg L⁻¹ × 178.8 cm × (10⁴ cm² / m²) × (1 L / 10³ cm³) × (10⁴ m² / ha) × (1 kg / 10⁶ mg)

= 59.7 kg SO₄²⁻ ha⁻¹

Convert to moles_c = $59.7 \text{ kg SO}_4^{2-} \text{ ha}^{-1} \times (1 \text{ mol}_c / 0.048 \text{ kg SO}_4^{2-}) = 1244 \text{ mol}_c \text{ SO}_4^{2-} \text{ ha}^{-1}$

Sulfate-S deposition = $59.7 \text{ kg SO}_4^{2-} \text{ ha}^{-1} \times (32 \text{ g S} / 96 \text{ g SO}_4) = 19.9 \text{ kg S ha}^{-1}$

Here is a shortcut for step 1

You can make a 10^6 jump from mg L^{-1} to kg ha^{-1} or from $\mu\text{mol}_c \text{ L}^{-1}$ to $\text{mol}_c \text{ ha}^{-1}$ with the following:

(annual weighted concentration) \times (annual precipitation) / 10

e.g., $3.34 \text{ mg SO}_4^{2-} \text{ L}^{-1} \times 178.8 \text{ cm} / 10 = 59.7 \text{ kg SO}_4^{2-} \text{ ha}^{-1}$

[Note that the units do not carry through in the computation above, so you have to know the final units]

- (c) If the mean annual volume-weighted pH of precipitation is 4.3 at this site, what is the approximate annual H^+ ion deposition in $\text{mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$?

Answer:

H^+ ion activity = $10^{-4.3} = 0.00005 \text{ mol H}^+ \text{ L}^{-1} = 5 \times 10^{-5} \text{ mol L}^{-1} = 50 \mu\text{mol}_c \text{ L}^{-1}$

Using the scaling relationship shown in the previous shortcut,

$(50 \mu\text{mol}_c \text{ H}^+ \text{ L}^{-1}) \times 178.8 \text{ cm} / 10 = 894 \text{ mol}_c \text{ H}^+ \text{ ha}^{-1}$

$23,100 \text{ cfs} \times (0.0283 \text{ m}^3 / \text{ft}^3) = 654 \text{ m}^3 \text{ s}^{-1}$

To compute the cm of flow, first calculate the drainage area in cm^2

Drainage area = $892 \text{ mi}^2 \times (2.59 \text{ km}^2 / \text{mi}^2) = 2310 \text{ km}^2$

$2310 \text{ km}^2 \times (10^6 \text{ m}^2 / \text{km}^2) \times (10^4 \text{ cm}^2 / \text{m}^2) = 2.31 \times 10^{13} \text{ cm}^2$

Now, convert the peak flow to cubic centimeters for a 24 hr. period

$654 \text{ m}^3 \text{ s}^{-1} \times (10^6 \text{ cm}^3 / \text{m}^3) \times (60 \text{ s} / \text{min}) \times (60 \text{ min} / \text{hr}) \times (24 \text{ hr.} / \text{day}) = 5.65 \times 10^{13} \text{ cm}^3 \text{ d}^{-1}$

Divide the volume of discharge by the area of the watershed

$(5.65 \times 10^{13} \text{ cm}^3 \text{ d}^{-1}) / (2.31 \times 10^{13} \text{ cm}^2) = 2.45 \text{ cm d}^{-1}$ per unit of watershed area

- (b) Retrieve the daily mean discharge data for the same river site during the period September 1, 1999 to September 30, 1999. Prepare a flow duration or exceedence graph for the September data using a log scale on the y-axis labeled Daily Runoff (cfs) and an arithmetic scale on the x-axis labeled Frequency of Runoff this High.

Answer:

Use Fig. 8.28 in Chap. 8 as an example for this problem.

Sample Problem in Hydrology

13. Visit the Water Resources of Maine website at <http://me.water.usgs.gov> and use the data base to survey hydrologic runoff records for the Aroostook River at Masardis (site number 01015800). I have previously asked students to find specific peak flow records in the online data base, but the USGS keeps changing the site and updating the runoff numbers, which means that the problem answer keeps changing to match changes in the data base. As a result, I am providing the runoff value below that is required to answer the problem.

- (a) During the period 1978–1998, the highest daily runoff flow occurred on 4/19/83 and reached a value of 23,100 cfs. For this watershed, the drainage area is 892 square miles. Express that peak flow in the following two different units: cubic meters per second (m^3/s), and cm of flow per day from the drainage basin. The last term expresses peak flow on a unit area basis similar to the measurement of precipitation inputs (e.g., so many cm of rainfall per 24-h day).

Answer:

The highest annual flow occurred on 4/19/83 and reached a value of 23,100 cfs

Sample Problems in Mineral Weathering

14. You have been hired to analyze data from a U.S. Forest Service watershed to determine the relative contributions of atmospheric deposition and weathering to stream cation exports. A previous vegetation study indicated that net annual biomass increment in the watershed is $1000 \text{ kg dry matter ha}^{-1} \text{ yr}^{-1}$ with mean weighted cation concentrations for the biomass increment of 0.5% Ca, 0.5% Mg, and 1.0% K (with no detectable Na). The hydrologic budget shows 100 cm of precipitation, 40 cm of evapotranspiration, and 60 cm of stream runoff. Estimate weathering in $\text{mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$ for each of the four major cations; show your work and state your assumptions.

	Ca	Mg	K	Na
Precipitation Chemistry				
Weighted mean, mg L^{-1}	0.20	0.06	0.20	0.12
Stream Chemistry				
Weighted mean, mg L^{-1}	2.00	0.30	0.78	1.15

Answer:

Assume that (i) weathering = sum of cations in runoff – cations in precipitation + cations in biomass increment, and

(ii) dry deposition and changes in stored soil cations are negligible.

Cations in the biomass increment of $1000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ are
 $\text{Ca} = 0.005 \times 1000 \text{ kg ha}^{-1} \text{ yr}^{-1} = 5 \text{ kg Ca ha}^{-1} \text{ yr}^{-1} \times (1 \text{ mol}_c / 0.02 \text{ kg Ca}^{2+}) = 250 \text{ mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Mg} = 0.005 \times 1000 \text{ kg ha}^{-1} \text{ yr}^{-1} = 5 \text{ kg Mg ha}^{-1} \text{ yr}^{-1} \times (1 \text{ mol}_c / 0.01215 \text{ kg Mg}^{2+}) = 411 \text{ mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{K} = 0.01 \times 1000 \text{ kg ha}^{-1} \text{ yr}^{-1} = 10 \text{ kg K ha}^{-1} \text{ yr}^{-1} \times (1 \text{ mol}_c / 0.039 \text{ kg K}^+) = 256 \text{ mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$

Cations in precipitation can be computed using the shortcut from Problem 12b.

$\text{Ca} = 0.2 \text{ mg L}^{-1} \times 100 \text{ cm} / 10 = (2 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.02 \text{ kg Ca}^{2+}) = 100 \text{ mol}_c \text{ Ca}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Mg} = 0.06 \text{ mg L}^{-1} \times 100 \text{ cm} / 10 = (0.6 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.01215 \text{ kg Mg}^{2+}) = 49 \text{ mol}_c \text{ Mg}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{K} = 0.2 \text{ mg L}^{-1} \times 100 \text{ cm} / 10 = (2 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.039 \text{ kg K}^+) = 51 \text{ mol}_c \text{ K}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Na} = 0.12 \text{ mg L}^{-1} \times 100 \text{ cm} / 10 = (1.2 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.023 \text{ kg Na}^+) = 52 \text{ mol}_c \text{ Na}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

Cations in stream runoff can also be computed using the shortcut from Problem 12b.

$\text{Ca} = 2 \text{ mg L}^{-1} \times 60 \text{ cm} / 10 = (12 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.02 \text{ kg Ca}^{2+}) = 600 \text{ mol}_c \text{ Ca}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Mg} = 0.3 \text{ mg L}^{-1} \times 60 \text{ cm} / 10 = (1.8 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.01215 \text{ kg Mg}^{2+}) = 148 \text{ mol}_c \text{ Mg}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{K} = 0.78 \text{ mg L}^{-1} \times 60 \text{ cm} / 10 = (4.68 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.039 \text{ kg K}^+) = 120 \text{ mol}_c \text{ K}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Na} = 1.15 \text{ mg L}^{-1} \times 60 \text{ cm} / 10 = (6.9 \text{ kg ha}^{-1} \text{ yr}^{-1}) \times (1 \text{ mol}_c / 0.023 \text{ kg Na}^+) = 300 \text{ mol}_c \text{ Na}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

Solving for $W = RO - P + B$ for each element

$\text{Ca} = 600 - 100 + 250 = 750 \text{ mol}_c \text{ Ca}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Mg} = 148 - 49 + 411 = 510 \text{ mol}_c \text{ Mg}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{K} = 120 - 51 + 256 = 325 \text{ mol}_c \text{ K}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

$\text{Na} = 300 - 52 + 0 = 248 \text{ mol}_c \text{ Na}^+ \text{ ha}^{-1} \text{ yr}^{-1}$

The total estimated cation weathering rate = $1833 \text{ mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$

15. Most experimental studies of weathering indicate that dissolution of feldspars increases as a function of solution acidity. Which solution would produce a faster initial rate of weathering: a solution of an organic acid such as fulvic acid at pH 4.85 or an aqueous solution of carbonic acid in equilibrium with a $p\text{CO}_2$ of 1.5%? Show your work and explain your answer.

Answer:

Use the carbonate equilibria in Chap. 7, substitute in the $p\text{CO}_2$ value given above, and solve the equations as follows:

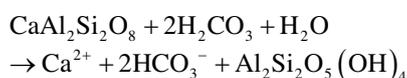
$$\begin{aligned} [\text{H}^+] \times [\text{HCO}_3^-] &= 1.36 \times 10^{-8} \times p\text{CO}_2 \\ &= 1.36 \times 10^{-8} \times 0.015 \\ &= 2.04 \times 10^{-10} \end{aligned}$$

Take the square root of the preceding value = 1.428×10^{-5}

Take the negative log of this value = $-\log [\text{H}^+] = \text{pH} = 4.85$

Based on this computation, both the carbonic acid and fulvic acid solutions have the same pH of 4.85. However, the fulvic acid would be expected to produce faster weathering, because fulvic acids not only provide H^+ ions for proton attack, but also contribute to chelation or complexation reactions that enhance chemical breakdown of minerals (see Chap. 7).

16. How much acid neutralizing capacity (ANC) is released during the weathering of 15.0 g of anorthite, a calcium feldspar (as illustrated below)? Show your computational steps, your ANC expression, and present your answer in mmol_c .



Answer:

$\text{ANC} = C_B - C_A$ or Sum of proton acceptors $- \text{H}^+$
 $= \text{Ca}^{2+} - 0$ or 2HCO_3^-

Formula weight of anorthite = $40 + 54 + 56 + 128 = 278 \text{ g}$

The percent Ca in anorthite = $40 / 278 = 0.143 = 14.3\%$

$15 \text{ g anorthite} \times 0.143 = 2.145 \text{ g Ca} = 2145 \text{ mg Ca}$

$2145 \text{ mg Ca} \times (1 \text{ mmol}_c / 20 \text{ mg Ca}) = 107.25 \text{ mmol}_c \text{ Ca}^{2+}$

If $\text{ANC} = \text{Ca}^{2+} - 0$, then $\text{ANC} = 107.25 \text{ mmol}_c$

Sample Problems in Element Cycling and Aqueous Chemistry

17. A forest calcium budget shows an annual Ca uptake by plants of 56 kg ha^{-1} . Focusing only on Ca and assuming that Ca^{2+} uptake is coupled with proton release from the plant root to the soil rhizosphere, what is the potential H^+ ion release associated with the annual uptake of Ca? Show your work and express your answer in $\text{mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$. How does this estimate compare with the average annual atmospheric wet deposition of H^+ ion in New England (assuming mean $\text{pH} = 4.3$ and annual precipitation = 100 cm)?

Answer:

$56 \text{ kg Ca}^{2+} \text{ ha}^{-1} \text{ yr}^{-1} \times (1000 \text{ mol}_c / 20 \text{ kg Ca}) = 2800 \text{ mol}_c \text{ Ca}^{2+} \text{ ha}^{-1} \text{ yr}^{-1}$

Uptake of Ca^{2+} requires an equivalent release of H^+ for charge balance = $2800 \text{ mol}_c \text{ ha}^{-1} \text{ yr}^{-1}$

H^+ ion in wet deposition = $10^{-4.3} = 0.000050 \text{ M L}^{-1} = 50 \text{ } \mu\text{mol}_c \text{ L}^{-1}$

Annual wet deposition can be computed with the shortcut in Problem 12b.

$$(50 \mu\text{mol}_c \text{H}^+ \text{L}^{-1}) \times 100 \text{ cm} / 10 = 500 \text{ mol}_c \text{ha}^{-1} \text{yr}^{-1}$$

Proton release from root uptake of Ca^{2+} is over five times greater than estimated wet deposition of protons.

18. Consider a watershed where the weighted annual mean concentration of chloride ion in precipitation is $25 \mu\text{mol}(-)\text{L}^{-1}$, the average annual stream runoff is 65% of precipitation inputs, and water storage is stable (i.e., steady-state on an annual basis). If you assume that chloride moves “conservatively” through the system without enrichment or depletion of mass (from uptake, mineralization, adsorption, or weathering), what is the final weighted annual mean concentration of Cl^- ion in stream water?

Answer:

ET concentrates 1.0 L of precipitation to 0.65 L of runoff. Thus, $25 \mu\text{mol}_c \text{Cl}^- \text{L}^{-1}$ in rainwater becomes $25 \mu\text{mol}_c \text{Cl}^-$ per 0.65 L in runoff. We compute the new concentration as follows:

$$25 \mu\text{mol}_c \text{Cl}^- \text{L}^{-1} \times (1.0 \text{ L} / 0.65 \text{ L}) = 38.5 \mu\text{mol}_c \text{Cl}^- \text{L}^{-1}$$

19. Consider a forest with an annual N uptake of $50 \text{ kg N ha}^{-1} \text{yr}^{-1}$, rainfall equivalent to 100 cm, and transpiration equivalent to 25% of rainfall. If we assumed that the forest acquires all of its N via passive bulk flow of transpirational water, what concentration of N in the soil water (as dissolved inorganic N) is necessary to allow the forest to take up $50 \text{ kg N ha}^{-1} \text{yr}^{-1}$? Express your answer as the solution concentration of inorganic N in mg L^{-1} . [Note that concentrations of inorganic N in field soil solutions are commonly <10% of the mean value you have calculated; this suggests that plants must use energy-dependent active uptake to meet their N demand].

Answer:

$$25\% \text{ of } 100 \text{ cm} = 25 \text{ cm} \times (10^4 \text{ cm}^2 / \text{m}^2) \times (1 \text{ L} / 1000 \text{ cm}^3) = 250 \text{ L H}_2\text{O m}^{-2}$$

$$\text{Plant uptake} = 50 \text{ kg N ha}^{-1} \text{yr}^{-1} \times (10^6 \text{ mg} / \text{kg}) \times (1 \text{ ha} / 10^4 \text{ m}^2) = 5000 \text{ mg N m}^{-2} \text{yr}^{-1}$$

Divide the nitrogen mass by the transpirational water volume

$$(5000 \text{ mg N m}^{-2} \text{yr}^{-1}) / (250 \text{ L m}^{-2}) = 20 \text{ mg N L}^{-1}$$

Sample Problems in Organic Matter Cycling

20. Data are presented below indicating the chemical composition of fresh leaf litter from three **northern tree species**. Use the data to predict which litter substrate would decay fastest. Rank the species from highest to lowest in order of their expected rates of decay. Show your logic or computations, and indicate the literature reference(s) upon which your rationale is based.

Species	%N	%Ca	%K	%Lignin
A	1.6	0.05	0.12	12.0
B	1.6	0.07	0.18	16.0
C	2.4	0.10	0.22	18.0

Answer:

Using the ratio of % lignin: % nitrogen, which Melillo et al. (1982) found is inversely related to litter decay rate, one would predict that A and C (with ratios of 7.5) would decay faster than B (ratio of 10.0).

21. What is the estimated annual CO_2 release from microbial decomposition of organic matter in the forest floor (O horizon) of an ecosystem under the following conditions? State any assumptions and express CO_2 release in $\text{g CO}_2 \text{m}^{-2} \text{yr}^{-1}$

- The forest floor is assumed to be in steady-state
- Forest floor mass is $50,000 \text{ kg organic matter ha}^{-1}$
- Annual inputs of detritus to the forest floor from litterfall + root mortality + throughfall DOM = $2500 \text{ kg organic matter ha}^{-1} \text{yr}^{-1}$

Answer:

If the forest floor is assumed to be in steady state, then inputs and outputs of detritus to this compartment are approximately equivalent.

Annual detrital inputs of $2500 \text{ kg organic matter ha}^{-1} \text{yr}^{-1} = 250 \text{ g m}^{-2} \text{yr}^{-1}$.

Assuming that detritus is roughly 50% carbon, we calculate that inputs and outputs are as follows:

$$250 \text{ g organic matter m}^{-2} \text{yr}^{-1} \times (0.5 \text{ g C} / 1 \text{ g organic matter}) = 125 \text{ g C m}^{-2} \text{yr}^{-1}$$

$$\text{Annual carbon dioxide release is } 125 \text{ g C m}^{-2} \text{yr}^{-1} \times (44 \text{ g CO}_2 / 12 \text{ g C}) = 458 \text{ g CO}_2 \text{ m}^{-2} \text{yr}^{-1}$$

22. Does leaf decay generate acidity or alkalinity? Consider a gram of decaying leaf with the composition shown below. Estimate the net ANC production that will likely result from complete microbial mineralization of this leaf with an initial mass of 1.0 g. Show three possible outcomes for this decomposition process based on the following assumptions:

- (1) assume that all of the N is only subject to ammonification, (2) assume that all of the N is subject to ammonification followed by 100% nitrification, and (3) assume all of the mineralized N is ultimately denitrified to dinitrogen, N_2 . Remember to consider the other elements as well.

Foliar concentrations (shown below) in parts per thousand in a leaf weighing 1.0 g

Carbon = 480	Nitrogen = 7	Sulfur = 2
Calcium = 8	Potassium = 4	Magnesium = 1

Answer:

Charge associated with each element in its ionic form:

$$\begin{aligned}
 7 \text{ mg N} \times (1 \text{ mmol}_c / 14 \text{ mg}) &= 0.5 \text{ mmol}_c \\
 2 \text{ mg S} \times (1 \text{ mmol}_c / 16 \text{ mg}) &= 0.125 \text{ mmol}_c \\
 8 \text{ mg Ca} \times (1 \text{ mmol}_c / 20 \text{ mg}) &= 0.4 \text{ mmol}_c \\
 4 \text{ mg K} \times (1 \text{ mmol}_c / 39 \text{ mg}) &= 0.1025 \text{ mmol}_c \\
 1 \text{ mg Mg} \times (1 \text{ mmol}_c / 12.15 \text{ mg}) &= 0.08 \text{ mmol}_c \\
 \text{Use ANC} &= C_B - C_A
 \end{aligned}$$

Case 1 with ammonification

$$\begin{aligned}
 (0.5 \text{ mmol}_c \text{ NH}_4^+ + 0.4 \text{ mmol}_c \text{ Ca}^{2+} + 0.1025 \text{ mmol}_c \text{ K}^+ + \\
 0.08 \text{ mmol}_c \text{ Mg}^{2+}) \\
 - (0.125 \text{ mmol}_c \text{ SO}_4^{2-}) \\
 = 0.96 \text{ mmol}_c \text{ ANC}
 \end{aligned}$$

Case 2 with nitrification

$$\begin{aligned}
 (0.4 \text{ mmol}_c \text{ Ca}^{2+} + 0.1025 \text{ mmol}_c \text{ K}^+ + 0.08 \text{ mmol}_c \text{ Mg}^{2+}) - \\
 (0.5 \text{ mmol}_c \text{ NO}_3^- \\
 + 0.125 \text{ mmol}_c \text{ SO}_4^{2-}) \\
 = -0.04 \text{ mmol}_c \text{ ANC}
 \end{aligned}$$

Case 3 with denitrification

$$\begin{aligned}
 (0.4 \text{ mmol}_c \text{ Ca}^{2+} + 0.1025 \text{ mmol}_c \text{ K}^+ + 0.08 \text{ mmol}_c \text{ Mg}^{2+}) \\
 - (0.125 \text{ mmol}_c \text{ SO}_4^{2-}) \\
 = 0.46 \text{ mmol}_c \text{ ANC}
 \end{aligned}$$

Sample Problems on Element Budgets

23. Use the data below to estimate how much calcium is exported from this watershed in a 1-year time period. Express your answer in moles of charge ($\text{mol}_c \text{ yr}^{-1}$) and indicate any assumptions you made. (note that cfs = cubic feet per second)

Month	Mean daily flow (cfs)	Mean Daily Ca concentration (mg L^{-1})
J	1000	3
F	1500	3
M	1200	3

A	4000	2
M	6000	2
J	3000	3
J	500	5
A	500	6
S	2000	3
O	4000	3
N	7000	2
D	1000	2

Answer:

Convert each mean daily flow to metric using $\text{cfs} \times (0.0283 \text{ m}^3 / \text{ft}^3)$ and scale this to a monthly value by multiplying by $(60 \text{ s} / \text{min}) \times (60 \text{ min} / \text{hr}) \times (24 \text{ hr} / \text{day}) \times \text{days in the month}$. Convert this value to liters per month, multiplying $\text{m}^3 \text{ mo}^{-1}$ by $1000 \text{ L} / \text{m}^3$, convert mean Ca concentrations to charge equivalents by multiplying $\text{mg Ca L}^{-1} \times (1 \text{ mol}_c / 20,000 \text{ mg})$, and calculate monthly Ca export by multiplying monthly discharge in liters per month times Ca concentration in $\text{mol}_c \text{ L}^{-1}$. Finally, sum up the 12 monthly values for Ca export to obtain an estimate of annual Ca export of $2.96 \times 10^8 \text{ mol}_c \text{ yr}^{-1}$. Use a spreadsheet to simplify this computation.

24. Consider a forest soil where the subsurface pool of soil organic matter contains $150,000 \text{ kg C ha}^{-1}$ and decays at an annual rate of $0.5\% \text{ yr}^{-1}$. What is the mean residence time of this carbon pool and how much carbon as root detritus and DOM must be transferred into this pool each year (in units of $\text{g C m}^{-2} \text{ yr}^{-1}$) to maintain it at steady-state? How does this estimate compare with reported values of fine root biomass and turnover?

Answer:

$$\begin{aligned}
 150,000 \text{ kg C ha}^{-1} \times 0.005 &= 750 \text{ kg C ha}^{-1} \text{ yr}^{-1} \\
 \text{Mean residence time} &= \text{Pool size} / \text{loss rate} = 150,000 / 750 = 200 \text{ yr}
 \end{aligned}$$

$$\text{Annual detrital input} = 750 \text{ kg C ha}^{-1} \text{ yr}^{-1} \times (1000 \text{ g} / \text{kg}) \times (1 \text{ ha} / 10^4 \text{ m}^2) = 75 \text{ g C m}^{-2} \text{ yr}^{-1}$$

As shown in Chap. 5, live root biomass at a depth of 10–40 cm can be in the range of 100 to 150 g m^{-2} and turnover rates can be as high as 100% per year.

Glossary

- Acid** a proton donor capable of acidifying an aqueous solvent
- Acid, Strong** an acid that ionizes readily to release virtually all of its protons
- Acid, Weak** an acid that ionizes partially to produce an equilibrium between bound and free protons
- Acid, Mineral** an acid that contains no hydrocarbons (e.g., sulfuric acid)
- Acid, Organic** an acid containing hydrocarbons (e.g., citric acid)
- Acid-Forming Precursor** a compound that can be readily converted to an acid
- Acid-Forming Salt** a substance such as ammonium sulfate that can be metabolized by microbes to form a strong acid (in this case, nitric acid generated by nitrification)
- Acid Ionization Constant** an equilibrium constant describing the extent of proton dissociation characteristic of a specific acid
- Acid Neutralizing Capacity (ANC)** the capacity of a substance or mixture to react with an acid to form a neutral salt (ANC is often referred to as alkalinity)
- Acidic Deposition** the transfer of acids and acid-forming compounds from the atmosphere to Earth
- Acidic Precipitation** precipitation with a pH below the carbonic acid equilibrium of roughly pH 5.6
- Acidity (Free and Bound)** free acidity is the activity of H⁺ ions in solution, whereas bound acidity is the quantity of titratable protons in a compound
- Actinorhizal** N fixing bacteria of the genus *Frankia* that associate with roots of woody plants
- Active Transport** the movement of an element or substance across a membrane with the assistance of an energy input, usually in the form of ATP
- Activity** the effective concentration of ions in a solution corrected for the influence of ionic strength
- Adsorption** the electrostatic attraction of a charged cation or anion to a surface with an opposite charge
- Aeolian** a deposit of fine sediments originating from wind-borne transport
- Aerobic** conditions with suitable oxygen present that electrons can be passed to oxygen as the terminal acceptor during metabolism
- Aerosol** an airborne microscopic particle
- Airshed** the area that contributes atmospheric emissions to downwind receptor watersheds
- Alicyclic** hydrocarbon molecules in which carbon chains link to form rings
- Aliphatic** hydrocarbon compounds composed of chains of carbon atoms
- Alkali Metal** a monovalent cation found in the first column of the Periodic Table
- Alkaline Earth Metal** a divalent cation in the second column of the Periodic Table
- Alkalinity** the sum of proton acceptors in solution (concentration of substances capable of neutralizing acidity)
- Alkaloid** a heterocyclic compound containing nitrogen that is produced by secondary metabolism in plants and acts as a toxin against herbivores
- Alkane** hydrocarbon containing only single bonds between carbon atoms
- Alkene** a hydrocarbon with one or more double bonds between carbon atoms
- Alkyne** a hydrocarbon containing one or more triple bonds between carbon atoms
- Allelopathic Substance** a potentially toxic organic substance released by plants to inhibit other competitors
- Alluvial** transported and deposited by water
- Ambient Ozone** the prevailing background concentration of ozone in the environment
- Ammonification** transformation of organic nitrogen (e.g., amino N) into NH₃
- ANC** see the definition for acid neutralizing capacity
- Anaerobic** in the absence of oxygen
- Anion** ion with negative charge
- Anion Adsorption** the attraction of a negatively charged ion toward a surface with a positive charge
- Anoxic** lacking oxygen

- Apoplast** the continuum of cell walls and extracellular spaces in a plant
- Aridisol** soils found in arid regions where moisture is limiting for plant growth and soil development
- Aromatic** hydrocarbon molecules containing six-membered rings each with three C-C double bonds
- Ash-Free Organic Matter** an estimate of the organic matter content of a sample, excluding the mineral ash remaining after high temperature combustion
- Assimilation** conversion or incorporation of nutrients into living cells or tissues
- Assimilatory Nitrate Reduction** metabolic reduction of nitrate within an organism to permit assimilation of the nitrogen into amino-N for protein synthesis
- Assimilatory Sulfate Reduction** metabolic reduction of sulfate ions within an organism to permit assimilation of the resulting reduced S into amino acids and proteins
- Atmospheric Deposition** the transfer of wet, dry, or gaseous substances from the atmosphere to the surface of the Earth
- Atmospheric Residence Time** the time period during which a substance remains in the atmosphere before returning to Earth
- Atomic Radius** a measure of the size of an atom with its electron cloud
- Available Water** the amount of water held in a soil between the field capacity and the wilting point
- Base Cation** cation (other than H^+ or ionic aluminum) capable of combining with OH^- to form a base
- Baseflow** river or stream runoff sustained by groundwater in the absence of precipitation or snowmelt
- Base Saturation** percentage of cation exchange capacity (CEC) filled with nutrient base cations (i.e., Ca, Mg, K, Na)
- Bidentate Chelate** a complex in which a ligand binds through two donor atoms to a metal ion
- Biogenic Gas** a gas that is produced or generated by a living organism
- Biogeochemistry** analysis of the patterns and processes by which nutrients and other biologically active elements and compounds interact with living organisms and circulate in the biosphere
- Bound Acidity** protons on weakly acidic functional groups that are not dissociated at ambient pH
- Brown Rot** a type of wood decay caused by Basidiomycete fungi that causes wood to become brittle
- Bulk Precipitation** precipitation collected in an open plastic funnel that includes wet deposition plus an undetermined amount of dryfall particles
- C-3 Plant** a plant such as a maple that is adapted to mesic conditions and forms two 3-carbon products as a result of the initial stage of carbon fixation
- C-4 Plant** a plant such as maize that is adapted to sunny drier environments and forms a 4-carbon compound as the initial product of carbon dioxide uptake
- C:N Ratio** an ecological indicator calculated by dividing the carbon mass or molar concentration by the nitrogen mass or molar concentration
- Calibration** a phase of model building in which model parameters are adjusted to improve the accuracy of outputs and predictions
- Calvin Cycle** the dark reaction in photosynthesis that consumes ATP and NADPH in order to fix CO_2
- Canopy Interception** the interception and retention of wet precipitation by foliage in the forest canopy
- Canopy Leaching** the removal of nutrient ions or solutes from foliage by rainwater passing over the leaves or needles
- Canopy Throughfall** the solution that results as precipitation washes through the foliage and branches of a forest canopy
- Canopy Washout** removal of dry deposited substances from a forest canopy by wet deposition
- Carbon-Bonded Sulfur** atoms of sulfur that are bonded directly to carbon in a molecule
- Carbon: Element Ratio** the relative proportions of carbon and any other element in a sample
- Carbonic Acid** an acid formed from the dissolution of CO_2 in water to form H_2CO_3
- Carboxyl** a functional group composed of $COOH$
- Catchment** the drainage area that collects water feeding into a stream, river, or lake
- Cation** ion with a positive charge
- Cation Adsorption** attraction of a positively charged ion to a surface with a negative charge
- Cation Exchange** the reversible interchange between a cation in solution and a cation adsorbed on the surface of a negatively charged colloid or cellular structure
- Cation Exchange Capacity** the amount of adsorbed cations that can be retained by a solid phase exchanger (expressed in $cmol(+)/kg$)
- CEC** see the definition for cation exchange capacity, which is abbreviated CEC
- Charge Balance** the equivalence between cations and anions in a system
- Charge Density** the density of ionic charge relative to ionic radius
- Charge Equivalents** moles of charge in a sample
- Chelate** a stable type of coordination complex in which a metal binds to multiple functional groups in a single multidentate ligand
- Cheluviation** a soil leaching process in which metallic ions are mobilized and are transported by organic acids that form chelates with the metals
- Chemical Denudation Rate** the rate at which solutes are removed from a watershed in stream runoff
- Chemical Ecology** a field of science focused on the influence of chemical interactions on ecology

- Chemoautotroph** a microorganism that uses carbon dioxide as a source of carbon and reduced inorganic substances as an energy source
- Chlorosis** yellowing of a leaf or needle as a result of plant stress
- Clay (1:1 and 2:1)** an aluminosilicate mineral composed of tetrahedral and octahedral sheets
- Cloud Condensation** formation of a moisture droplet around a nucleus such as a microscopic particle
- Coarse Woody Debris (CWD)** woody detritus such as branches and tree boles
- Colloid** a microscopic particle such as clay or a humus particle that may have a surface electric charge
- Colluvial** material moving downslope under the influence of gravity
- Complexation** a process by which a monodentate or multidentate ligand binds covalently to a cation
- Complexing Ligand** an anionic molecule that donates electrons to form a coordination complex with a metal
- Concentration** moles of a substance per unit volume or mass
- Conductivity** a measure of the electrical conductance of a water sample; conductivity increases with the total concentration of ions in solution
- Congruent Dissolution** mineral dissolution in which the solid phase is transformed completely to solutes
- Conservative Ion** an ion that moves without significant retention or enrichment through a watershed
- Coordinate Bond** a covalent bond in which a ligand donates electrons to an electron-deficient cation
- Coordination Complex** a compound containing a metal ion bonded to surrounding molecules or ions that act as ligands
- Coulombic Attraction** attraction based on electrical charges and electrostatic forces
- Counter Ion** an ion that balances the opposite charge of an adjacent ion
- Covalent Bond** a chemical bond in which electrons are shared between nuclei of adjacent atoms
- Crown Leaching** removal of dissolved solutes from plant foliage in a forest by precipitation moisture
- Cucurbitacin** a plant defensive compound that deters herbivores by imparting a bitter taste to leaves
- Cynaogenic Glycoside** a nitrogenous plant toxin that is metabolized by insects to form hydrogen cyanide
- Decay Constant** an estimate (k) of the fractional rate of decay per year
- Decomposition** the decay of organic matter or detritus as a result of physical leaching and microbial metabolism
- Degree Days** sum of daily temperatures above freezing ($0\text{ }^{\circ}\text{C}$) for the year
- Denitrification** the reduction of nitrate by microbial organisms; complete denitrification produces N_2 gas
- Denudation Rate** the rate at which weathering processes remove mineral elements from a watershed
- Depleted (in Heavy Isotope)** the composition of an element is deficient in heavy isotope compared to a standard reference material, resulting in a “light” isotopic signature
- Deposition (Dry and Wet)** the transfer of wet, dry, or gaseous substances from the atmosphere to the surface of the Earth
- Deposition Velocity** the rate of transfer of material from the atmosphere to surfaces on Earth
- Deterministic Model** a mathematical model in which quantitative relationships and variables are specified, rather than being based on probabilities
- Detritus** dead organic matter
- Diffusion** movement of molecules from a region of higher to a region of lower concentration
- Dissimilatory Nitrate Reduction** anaerobic reduction of nitrate ion to ammonium ion by microbes that use nitrate as an electron sink during metabolism
- Dissimilatory Sulfate Reduction** anaerobic reduction of sulfate ion to sulfide ion by microbes that use sulfate as a terminal electron acceptor during metabolism
- Dissolution** transformation of a solid phase substance into solutes
- Disturbance** an event that removes or damages organisms and opens colonization space in an ecosystem
- DOC** dissolved organic carbon that may give a yellow or brown hue to natural waters
- DOM** dissolved organic matter (includes DOC and other components of soluble organic matter)
- Drainage Network** the branching dendritic system of streams and rivers in a drainage basin
- Dry Deposition** the transfer of dry particles, aerosols, or gases to receptors on Earth
- Dryfall** particles that fall from the atmosphere under the influence of gravity
- Ecological Biochemistry** study of the influence of secondary metabolites on ecological interactions
- Ecosystem** a functional ecological unit composed of interacting organisms and their environmental surroundings. The boundaries that define an ecosystem can be relatively sharp – as in the case of a watershed or a lake ecosystem – or they may be more subtle or subjective in nature (e.g., an estuarine ecosystem with fluctuating tidal ranges and salinity gradient). In hierarchical terms, an ecosystem represents a high-level organizational unit that incorporates population-based and community-based processes into an environmental framework. Within a given ecosystem, we can distinguish structural and functional patterns and processes involving linked biotic and abiotic components.
- E_h** the redox potential of a system measured with a platinum electrode

- Eddy Covariance** a biophysical technique based on concentration gradients and wind parameters that is used to estimate gas exchanges between the atmosphere and surfaces on Earth
- Effective CEC** cation exchange capacity estimated as the sum of exchangeable cations in a field soil, rather than the potential exchange capacity measured by ammonium adsorption at pH 7 or greater.
- Electrical Conductivity** a measure of the electrical conductance of a water sample; conductivity increases with the total concentration of ions in solution
- Electrical Neutrality** the principle dictating that opposite charges in a system must balance
- Electronegative** elements such as oxygen that attract bonding electrons and become negatively charged
- Element Increment** the annual increase in element mass incorporated into new biomass production
- Element ratio** ratio of one element to another expressed in mass or molar units
- Eluviation** removal of metal ions from a soil horizon under the influence of acid leaching
- Enriched (with Heavy Isotope)** the composition of an element is isotopically “heavy” and contains a higher proportion of heavy isotope than a reference standard
- Equilibrium** a condition in which rates of forward and backward reactions are equivalent
- Equilibrium Constant** the value of the ratio of equilibrium concentrations of products to equilibrium concentrations of reactants, each raised to a power equal to its stoichiometric coefficient
- Equivalent Charge** moles of charge associated with a particular ion
- Equivalent Weight** the mass of an element or substance that will displace or otherwise react with one mole of hydrogen (1.008 g) or one half mole of oxygen (8.00 g)
- Ester** a hydrocarbon in which a side group bonds to the oxygen atom of a carbonyl group
- Evaporation** transfer of water from the liquid phase to the vapor phase in response to heat input
- Evapotranspiration** a term describing the combined processes of evaporation and plant transpiration that account for water transfer from a watershed to the atmosphere
- Exchangeable Acidity** the protons adsorbed to the soil exchange complex that act as a reservoir of acidity
- Facultative** a generalist micro-organism that can switch between aerobic respiration and fermentation as a function of redox conditions
- Felsic** rock minerals that are rich in aluminum and silica
- Fermentation** occurs under conditions of lower redox when the process of glycolysis terminates in the formation of lactic acid or ethanol as the end-product of pyruvate synthesis
- Field Capacity** the amount of water held by a soil at a tension of -0.03 MPa, after the soil has been saturated and free gravitational water has drained from the pores
- Fine Roots** the smallest plant roots (usually less than 1 mm diameter) that are most active in absorption of water and nutrients
- Fine Root Production** annual growth of new fine roots (generally less than 1 mm in diameter)
- First Order** a chemical reaction for which the rate is proportional to a reactant concentration raised to the power of 1 (e.g., the exponent is 1)
- Flavonoid** family of flower pigments based on the flavone skeleton and containing a phenolic-OH group
- Flow Path** the pathway followed by water as it drains through a watershed and into groundwater or surface water
- Flux** refers to the transfer of mass into or out of a system
- Fly Ash** residual ash material resulting from coal combustion that emits from a power plant stack
- Foliar Stippling** necrotic spots that develop on plant leaves or needles
- Forcing Factor** in terms of the heat budget of the Earth, a forcing factor contributes either to a warming or cooling of the atmosphere by either reinforcing or offsetting the input of solar energy
- Forest Floor** the uppermost soil horizon or O horizon in a forest that is primarily composed of leaf litter and decaying organic matter
- Fragipan** a soil layer that is very dense and acts as a barrier to root and moisture penetration
- Free Acidity** the acidity resulting from proton dissociation by strong acids or acidic functional groups; this is the acidity measured by a pH probe
- Fulvic Acid** a polycarboxylic organic acid that is soluble in basic and acidic solutions, contains a mixture of aliphatic and aromatic structures, and has a molecular weight of < 2000 daltons
- Functional Group** an atom or group of atoms that imparts specific chemical properties to an organic compound
- Glacial Till** a glacial deposit composed of unsorted sediments and rocks
- Gleying** soil formation under saturated conditions and poor drainage, resulting in reducing conditions and limited differentiation of soil horizons
- Gravitational Settling** vertical transfer of particles from the atmosphere or a water column to a solid surface
- Gross Mineralization** the total microbial conversion of organic N to ammonium-N over a given time period
- Gross Production** total fixation of carbon by primary producers in a given time period
- Groundwater** water that is stored beneath the ground surface in a watershed, ultimately contributing to stream base flow

- Heavy Fraction** a dense soil fraction composed of organic matter aggregated with mineral material
- Heavy Metal** a metal such as lead, mercury, or cadmium with a large atomic mass and a potential for biological toxicity
- Henry's Law Constant** describes the solubility of a gas in water as a function of the partial pressure of that gas
- Hill Reaction** the light reaction in photosynthesis that combines the photolysis of water with the production of ATP and NADPH
- Histosol** a soil composed primarily of organic matter such as peat
- Humic** characterized by or derived from partially decomposed organic matter that is generally acidic
- Humic Acid** an aromatic polycarboxylic organic acid that is soluble in base, but is insoluble below pH 1
- Humic Colloid** a microscopic soil particle composed of decayed or humified organic matter
- Humus** organic detritus that has undergone decomposition and has a high surface area to volume ratio
- Hydrogen Bonding** a chemical bond that occurs when an electronegative atom serves as an electron donor and partially shares its nonbonding electrons with a polarized hydrogen atom
- Hydrograph** a graphical representation of the variable water discharge over time by a stream or river
- Hydrolysis** reaction of a molecule or compound with water
- Hydrolyzed** a compound or molecule that has reacted with water to dissolve or to ionize
- Hydrophilic** a polar substance, molecule, or functional group that is "water loving" and is readily soluble in water
- Hydrophobic** a non-polar substance, molecule, or functional group that is not readily soluble in water
- Hydroxyl** an OH functional group or OH⁻ ion
- Hyetograph** a graphical representation of rainfall patterns over time at a particular location
- Hyphae** the filaments that comprise the body of a fungus
- Illuviation** a soil process in which leached solutes and colloids accumulate in subsoil mineral horizons
- Immobile Nutrient** a nutrient that is not readily transported from one tissue to another by the phloem
- Immobilization** this occurs when a soluble ion is assimilated into microbial biomass
- Impaction** occurs when a moving particle or aerosol encounters a surface, loses momentum, and deposits on the surface
- Inceptisol** a soil formed in fine parent material where conditions do not permit sufficient leaching and translocation to generate distinctive subsurface horizons
- Incongruent Dissolution** transformation of a mineral into solutes plus a residual solid phase
- Infiltration** movement of water into and through a soil or geologic deposit
- Interception** the retention or storage of precipitation by plant foliage, prior to generation of throughfall
- Interflow** water moving horizontally through soil layers toward a downslope drainage channel
- Ion Activity** the "effective" concentration of an ion in solution calculated as a function of ionic strength using an ion activity coefficient
- Ion Exchange** the reversible movement of ions between an aqueous solution and a solid phase charged surface such as an aluminosilicate clay
- Ion Ratio** the abundance or concentration of one ion compared to another in a ratio or fraction
- Ionic Bond** a bond between oppositely charged ions
- Ionic Strength** a measure of the total concentration of ions in solution based on molarity and ionic charge
- Isoelectric Point** the pH at which an amphoteric substance is electrically neutral and exhibits no net positive or negative charge
- Isomorphic Substitution** a process by which an ion substitutes for another ion of similar size in the lattice of a clay; the new ion may have a different electrical charge than the original ion
- Isotope Dilution** an experimental technique using stable isotopes in which a reaction rate is estimated by adding a heavy isotope tracer to a system and measuring the rate at which that isotope is diluted by background generation of a molecule containing the light isotope of that element.
- Kinetic** refers to the rate of a chemical process
- Lacustrine** sediments derived from a lake environment
- Leachate** a solution that has contacted a solid phase and has gained solutes as a result of that interaction
- Leaching** removal of ions and other solutes from solid phases by water
- Leaf Area Index** ratio of projected leaf area per unit of ground area beneath a forest canopy
- Ligand** an ion or molecule that shares electrons with a metal atom
- Light Fraction** a low density mineral-free soil fraction composed of decayed plant material and microbial biomass
- Lithic Element** an element that occurs in minerals and rock
- Litterfall** recycling of foliage and branches from a plant community back to the soil surface
- Long-Range Transport** transport of substances such as pollutants over long distances in the atmosphere
- Lysimeter** a sampling device intended to collect soil water for chemical analysis
- Macronutrient** a chemical that an organism must acquire in relatively large amounts for nutrition
- Macropore** a large soil pore through which gravitational water moves

- Mafic** rock minerals that are rich in magnesium and iron
- Mass Balance** a systematic analysis of the inputs and outputs of elements to a system based on mass
- Mass Fractionation** separation or discrimination of isotopes based on differences in mass
- Methanogenesis** the production or generation of methane by microbes known as methanogens
- Methanotroph** a microbial organism that consumes and oxidizes methane as an energy source
- Methylation** addition of a methyl group ($-\text{CH}_3$) to an atom or molecule (as in mercury methylation)
- Microcosm** a small bench-top sized replica of an ecological system
- Micronutrient** a chemical that an organism requires in small amounts for nutrition
- Micropore** a small or microscopic soil pore through which capillary water moves
- Mineral Acid** an acid such as nitric, hydrochloric, or sulfuric that lacks carboxylic functional groups
- Mineralogy** the mineral composition (e.g., quartz or biotite) of soil, surficial material, or bedrock
- Mineral Soil** usually refers to the subsoil that is composed almost entirely of mineral grains and clays
- Mineral Weathering** chemical breakdown of solid phase minerals to release weathering products
- Mineralization (Gross and Net)** transformation of organically bound elements to inorganic forms that are available for biological uptake
- Mobile Anion** a negatively charged ion that moves relatively freely through the soil without major retention by biotic or abiotic mechanisms
- Model** a qualitative conceptual or quantitative numerical representation of a process, pattern, or system
- Monodentate Ligand** a molecule containing a single functional group capable of sharing electrons with a metal ion
- Multidentate Ligand** a molecule containing two or more functional groups capable of sharing electrons with a metal ion through coordinate bonds
- Mycorrhizal Fungi** fungal species that form symbiotic associations with plant roots
- Necromass** the mass of dead tissue
- Necrosis** death of tissue through disease or stress
- Net Ecosystem Production (NEP)** the amount of gross primary production remaining after subtracting autotrophic and heterotrophic respiration
- Net Mineralization** microbial gross mineralization minus microbial immobilization of ammonium-N
- Net Primary Production (NPP)** gross primary production minus autotrophic respiration
- New water** water that has recently entered a watershed as precipitation, moves laterally as quickflow, and rapidly appears as stream runoff
- Nitrate Reduction (assimilatory and dissimilatory)** reduction of nitrate ion to a less oxidized state such as NO or N_2
- Nitrification** oxidation of ammonium ion to nitrate by micro-organisms
- Nitrogen Fixation** transformation of atmospheric dinitrogen (N_2) to ammonia (NH_3)
- Nitrogen Saturation** a condition in which the supply of inorganic N exceeds biological demand for N
- Nitrogenase** the enzyme that catalyzes the process of N fixation
- Non-polar** a molecule that lacks strong electronegative or electropositive attributes and is consequently insoluble or poorly soluble in water
- Nuclide** a nucleus of a specific isotope of an element
- Nutrient Requirement** annual element increment associated with the production of new shoots, roots, and current foliage
- Nutrient Uptake** annual plant increment of an element accumulated in new woody tissues plus annual losses of that element through litterfall, root turnover, leaching, and net stemflow.
- Nutrient Use Efficiency** amount of biomass produced per unit of a given nutrient
- Obligate** an organism that is a specialist in terms of only surviving under a specified set of conditions
- Old water** water that has infiltrated the soil over a period of time and has reacted with the soil matrix
- Operational Definition** a definition that is not unique, but which is established by a particular set of operating procedures
- Order of Reaction** the power to which the concentration of a reactant is raised in a rate law
- Organic Acid** a hydrocarbon that contains at least one acidic carboxyl group
- Orographic Precipitation** enhanced precipitation resulting from adiabatic cooling associated with high elevation mountains
- Osmosis** movement or diffusion of water across a semi-permeable membrane
- Osmotic Potential** a component of water potential that is proportional to the concentration of solutes in a solution
- Oxidation** donation of an electron from an atom
- Oxisol** a tropical soil that is highly weathered and contains a large accumulation of iron oxides
- Parent Material** the geologic material in which soil formation occurs
- Peak Flow** the period of runoff when water level and velocity are elevated by stormflow or snowmelt
- Pedogenesis** soil formation
- Periodic Table** a chart showing relationships among elements based on mass and electron shells
- Permanent Charge** electrical charge on a clay colloid that results from isomorphic substitution in the lattice and is independent of changes in pH

- pH-dependent** a process that varies as a function of the acidity or pH conditions in the environment
- Phenology** study of seasonal changes in the morphology, physiology, and behavior of living organisms
- Piston Flow Displacement** movement of water through soils in response to hydrostatic pressure from above
- Plasmalemma** membrane surrounding the cytoplasm of a plant cell
- Platinum Electrode** a probe that is used to estimate redox potential
- Podzolization** a soil forming process that occurs in well-drained temperate forest soils where climatic conditions are cool and mesic and organic acid leaching is a major driver of pedogenesis
- Polar Covalent Bond** a covalent bond in which the shared electrons are preferentially attracted toward a more electronegative atom
- Pool** a reservoir or storage compartment in an ecosystem containing accumulated elements or substances
- Precipitation** removal of ions from solution through bonding and formation of insoluble colloids
- Precipitation (Wet)** liquid water transferred to a watershed from the atmosphere via gravity
- Preferred Pathway** a pathway followed by drainage water moving through macropores in the soil
- Primary Mineral** a mineral such as quartz, feldspar, or hornblende that originates from magma
- Primary Production** energy assimilation and biomass production by plants; gross primary production (GPP) is the total energy assimilated by plants, whereas net primary production (NPP) is the plant biomass remaining after subtracting plant respiration
- Priming Effect** the vigorous response of microbial decomposers to an input of fresh organic detritus
- Production Efficiency** the ratio of plant net primary production (NPP) divided by GPP
- Products** in a chemical reaction, products occur on the right side of the reaction
- Proficient Plant** a plant that lowers its concentrations of N and P to very low levels through resorption
- QA/QC** this abbreviation refers to quality assurance and quality control in measurements and analysis
- Quickflow** water that moves quickly through a watershed and into a stream channel or lake
- Quinone** an aromatic hydrocarbon that contains an oxygen atom double-bonded to a carbon atom
- Radiative Forcing** the extent to which a substance or process acts to cool or to warm the heat budget of the Earth
- Rainout** removal of gases and particles from a cloud during rain droplet formation and deposition
- Reactants** in a chemical reaction, reactants occur on the left side of the reaction
- Reaction Rate** a measure of the rate at which reactants interact to form products in a chemical reaction
- Recharge** a process by which infiltrating water replenishes groundwater
- Redox** a measure of the oxidation or reduction status of a system
- Reduction** addition of an electron to an atom
- Residence Time** an estimate of the time an atom of a substance remains in a system before being replaced or removed
- Resorption** removal or retranslocation of an element from foliage to woody tissues prior to leaf drop
- Retranslocation** movement of an element from one plant sink to another sink via the phloem
- Rhizosphere** the soil zone immediately surrounding a plant root system and its associated mycorrhizae
- Riparian Zone** terrestrial zone located immediately adjacent to or on the banks of a stream, river, or other water body and subjected to periodic flooding
- Root Free Space** the apoplast on the exterior of a plant root into which ions diffuse from the rhizosphere
- Root Turnover** the processes of death, decay, and replacement of roots in a plant community
- Rubisco** an enzyme in the Calvin Cycle (ribulose biphosphate carboxylase) that catalyzes CO₂ fixation
- Sand** soil particles with diameters ranging from 0.05 to 2.0 mm
- Saprolite** a type of soil parent material composed of highly weathered and crumbling bedrock
- Saturated Flow** movement of gravitational water through soil macropores
- Saturated Soil Hydraulic Conductivity** the rate of vertical water infiltration into a soil under saturated conditions
- Saturated Zone** the soil horizons and surficial deposits in a watershed that are saturated with water
- Saturation Index** ratio of the ion activity product of two ions divided by the solubility product of the ions
- Scavenging Efficiency** the extent to which different forms of precipitation absorb or remove substances from the atmosphere
- Second Order Reaction** a chemical reaction for which the rate is proportional to a reactant concentration raised to the power of 2 (e.g., the exponent is 2)
- Secondary Compounds** usually refers to metabolites produced by secondary metabolism related to defense of the organism
- Secondary Mineral** a mineral such as a clay or metal oxide that is generated from the weathering products of primary minerals
- Senescence** the inherent aging and deterioration of foliage that precedes leaf or needle drop by perennial plants
- Sensitivity Analysis** a procedure used to test which parameters in a computer model are most or least influential in determining overall outputs or predictions

- Siderophore** a soluble organic substance released by plants that helps to increase the solubility of key plant nutrients such as iron in the soil
- Silt** soil particles with diameters ranging from 0.002 to 0.05 mm
- Sink** a system at any scale that acts as a place of accumulation for nutrients, matter, or energy
- Site Quality** the ability of a plot of land to provide resources to support the growth of organisms
- Sodic Mineral** a mineral containing appreciable amounts of the element sodium
- Soft Rot** the soft consistency of wood decayed by fungi that break down cell walls
- Soil Buffer Capacity** the ability of a soil horizon to resist changes in pH in response to added acid or base
- Soil Colloid** a microscopic soil particle such as a clay, metal oxide, or humus particle
- Soil Heavy Fraction** soil organic matter that is adsorbed onto mineral surfaces or sequestered in micro-aggregates
- Soil Horizon** a horizontal layer in a soil profile with distinctive physical and chemical features
- Soil Hydraulic Conductivity** the rate at which soil moisture moves through soil pores
- Soil Leaching** movement of solutes through soils in response to water infiltration
- Soil Light Fraction** fraction of soil organic matter that is relatively free of mineral material and includes plant and microbial detritus
- Soil Order** a major soil group such as an Oxisol that is defined by physical-chemical properties and climatic conditions
- Soil Organic Matter (SOM)** the detrital remains of plant, animal, and microbial biomass in soils
- Soil Respiration** efflux of carbon dioxide from soils that is derived from respiration by plant roots, soil animals, and microbes
- Soil Texture** a description of the relative proportions of sand, silt, and clay particles in a soil
- Source** place of origin for materials moving to a sink
- Spodosol** a major soil order characterized by a subsurface spodic B horizon
- Stable Isotope** an atom characterized by a specific number of protons and neutrons that is stable and does not normally disintegrate through radioactive decay
- State Variable** a parameter in a computer model describing the quantitative condition of a system component
- Steady State** a condition in which inputs and outputs are approximately equal in a system
- Stemflow** precipitation moisture that has moved from the forest canopy downward toward the ground following the stem or bole of the tree
- Stoichiometry** a description of the ratios of elements in cells, tissues, or organisms
- Stoichiometric Coefficient** in chemical notation, this integer precedes each reactant or product and indicates the relative numbers of moles of each molecule involved in a reaction
- Stomatal Conductance** the rate at which gas or water vapor is exchanged through stomatal pores; this varies with the size of the stomatal aperture
- Stream Order** the position of a stream in the hierarchy from small headwater streams to large rivers
- Stress** a biotic or abiotic constraint or influence that adversely affects critical life processes for organisms
- Strong Acid** a compound that readily dissociates in water to release acidifying protons
- Strong Mineral Acid** an acid such as nitric, hydrochloric, hydrofluoric, or sulfuric acid that generates extreme acidity
- Succession** an ecological process that occurs during the successive stages of maturation and ecological development following disturbance in a biological community
- Sulfate Reduction (Assimilatory and Dissimilatory)** reduction of sulfate ions to sulfide or other reduced species of sulfur as a result of electron transfers mediated by living organisms
- Surficial Deposit** usually refers to an accumulation of sediments or residuum overlying bedrock
- Surficial Geology** the study of surficial sedimentary deposits or residuum overlying bedrock
- Symplast** the pathway in plants for movement of water from cell to cell within the cytoplasm
- Throughfall** moisture derived from atmospheric deposition that passes through plant foliage in a forest canopy and drips to the ground
- Till** unsorted glacial debris that forms a specific type of surficial deposit with sandy features
- Total Acidity** the sum of free and titratable bound acidity in a compound with acidic functional groups
- Trace Metal** an element that occurs in low concentrations and belongs to the transition metal group in the Periodic Table
- Transpiration** transfer of water vapor from plant stomata to the atmosphere in response to a water potential gradient
- Ultisol** a major soil order found in warm humid climates, with a subsurface accumulation of clay
- Unreactive N₂** the triple-bonded dinitrogen gas that occurs at a concentration of 78% in the atmosphere
- Unsaturated Flow** movement of soil moisture in response to capillary forces and soil matric potential
- Unsaturated Zone** portion of soil profile and surficial deposits in a watershed where moisture content is below field capacity
- Unweighted Mean** the average computed as the sum of data points divided by the number of data points
- Validation** a process in which a model is independently confirmed or validated using new data

- Vapor Pressure Deficit** difference between the current air concentration of water vapor and the concentration of water vapor predicted at the dewpoint for that air temperature
- Variable Source Area** a zone in a watershed that quickly becomes saturated by rainfall or snowmelt and serves as a source for rapid interflow or saturated overland flow to a stream channel
- Volume Weighted Mean** a mean calculated by taking into account differences in sample volumes
- Washout** removal of dry deposition from a plant canopy by wet deposition; this term also refers to below-cloud scavenging of chemical substances
- Water Balance or Budget** an analysis of water inputs, outputs, and storage in a watershed
- Water Potential** a physical property that explains the movement of water in plants, other organisms, and soils; in plants, water potential is the sum of pressure potential and osmotic potential
- Watershed** the topographically defined area that collects wet deposition and drains into a stream or surface water system
- Water Stress** a condition characterized by a low water potential and water deficiency that may be accompanied by adverse physiological symptoms
- Weak Acid** a compound with a small acid dissociation constant that partially ionizes in water to release protons (an example is acetic acid or carbonic acid)
- Weathering** the physical or chemical breakdown of minerals
- Weighted Mean** a mean value that is calculated using differences in sample amounts to weight the proportional contribution of each sample concentration to the overall average
- Wet Deposition** the transfer of water droplets and solutes to receptors on Earth
- White Rot** a decay process caused by Basidiomycete and some Ascomycete fungi, giving wood a bleached appearance
- Wilting Point** the soil water potential (-1.5 MPa) at which water scarcity causes wilting in plants
- Zero Point of Charge** the pH at which a colloid has not net positive or negative electrical charge

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Index

- A**
Aboveground biomass, 61, 64, 154
Aboveground structure and function, 43–46
Acid ionization, 4
Acid neutralizing capacity (ANC), 11, 24, 58, 79, 87, 95, 121, 122, 127
Acid-base chemistry of plant uptake, 55, 56, 150
Acidic deposition, 21, 23, 57, 59, 76, 83, 87
Acidity, 11, 12, 16, 20, 22–25, 35, 37, 40, 58, 79, 89–92, 103, 108, 115, 119, 120, 122, 126, 135, 149
Acidity and weathering, 16, 23, 40, 89, 90, 92, 93, 149
Active transport, 54
Activity coefficient, 123
Actual evapotranspiration (AET), 71
Adsorption, 5, 12, 18–20, 23, 24, 27, 34, 57, 59, 67, 69, 73, 81, 83, 120, 123–128, 137, 149, 154
Alkali metals, 1
Alkaline earth metals, 1
Alkalinity, 11, 16, 58, 79, 87, 121, 122, 126, 127, 149
Alkaloids, 52, 53
Allelopathic compounds, 53
Aluminum antagonism and toxicity, 59
Aluminum cycle, 134, 135
Aluminum hydrolysis, 124
Ammonification, 34, 36
Anaerobic sulfate reduction, 24, 32, 37–39
Analysis of aqueous chemistry, 7, 119–129
Analysis of deposition, 23, 34, 55, 57, 73–79, 81, 82, 111, 154
ANC budgets, 127
ANC generation, 120, 126–128
Anion adsorption, 18–20, 120, 125
Anion mobility, 124, 125
Aqueous chemistry, 7, 119
Assimilatory nitrate reduction, 37
Assimilatory sulfate reduction, 38
Atmospheric chemistry, 73, 74
Atmospheric deposition, 20, 23, 28, 34, 40, 54, 55, 58, 61, 73–85, 97, 99, 131–137, 146, 149, 157
Atmospheric deposition models, 84
Atomic radius, 1
Available water, 16, 104
- B**
Base flow, 106, 116, 117
Base saturation, 14, 20–22, 24, 25
Belowground biomass, 61, 64, 145
Belowground plant structure, 43, 45, 46, 54, 57, 65, 66, 68, 133, 135, 159
Biogeochemical models, 141–150
Biomass allocation, 46
Bioremediation, 40
Brown rots, 67
Bulk precipitation, 76, 77, 80, 85
- C**
C:N ratios, 34, 35, 42, 66, 67, 70, 133, 157
C-3 and C-4 plants, 9
Calcium cycle, 87, 134
Calibration of a model, 142–144, 146, 150
Calvin cycle, 47, 48
Canopy interception, 101, 113, 114
Canopy throughfall, 57, 58, 66, 77, 81, 83, 108, 114, 125, 126, 133
Capillary tension, 104
Carbon allocation, 46, 52, 147
Carbon cycling, 9, 39, 51, 52, 59, 63, 141, 142
Carbon fixation, 43, 46, 142
Carbon isotopes, 9
Carbonic acids, 23, 90–93, 99, 122
Case studies of aqueous chemistry, 125–129
Cation exchange, 17, 18, 20, 28, 34, 83, 88, 94–96, 98, 100, 120, 121, 126, 137
Cation exchange capacity (CEC), 20, 21, 24, 25, 88
CENTURY model, 148–150
Charge balance, 7, 23, 28, 55, 78, 121, 127
Charge density, 1, 19
Chelate, 3, 22, 91
Chemical bonding, 1, 3
Chemical reactions, 3, 4, 11, 75, 123, 150
Chemical speciation, 123, 124
Chemical tracers in stream hydrology, 107–109
Chlorophyll, 3, 41, 42, 46, 48
Chronic N inputs, 155–157
Clay colloids, 17, 18, 87
Clays, 13–20, 23–25, 29, 34, 62, 87, 88, 93, 95, 96, 101, 104, 123
Clear-cut, 35, 64, 152, 153
Cloud water chemistry, 84
Coarse woody debris (CWD), 64, 65, 132, 151
Colloids, 17–20, 23, 54, 62, 87, 94, 104, 125
Complexation, 5, 12, 22, 23, 87, 92
Conductivity, 104, 105, 122
Controls on weathering rates, 89–93, 95–97
Coordination complexes, 3
Coulombic attraction, 3
Covalent bonds, 1, 3
Crown leaching, 57
Crown washout, 57
Cyanogenic glycosides, 52
- D**
Decay constant, 68, 69, 142
Decomposition, 12, 34, 37, 38, 43, 45, 55, 57, 61, 62, 64, 67–72, 131, 142, 148, 150, 153, 155, 157–159
Deforestation, 64, 152–154
Degree days, 71
Denitrification, 35, 36, 124, 125, 133, 137, 138, 150

- Denudation rate, 98, 99
 Deposition at a forest edge, 78, 81
 Deposition at Walker Branch, TN, 77, 85, 87, 107, 108, 133, 134, 136
 Deposition in North America, 14, 39, 63, 73, 77, 81–83, 112, 133, 134, 155, 157
 Deposition processes, 74–76, 81, 85
 Deposition velocity, 74, 75, 77
 Detrital cycling in plants, 57, 144, 145
 Detritus, 24, 34, 37–39, 54, 57, 61, 64–72, 91, 126, 132–134, 136, 138, 145, 153
 Diffusion, 6, 16, 54, 57, 74, 75, 91, 107, 114, 124
 Dissimilatory nitrate reduction, 36, 37
 Dissimilatory nitrate reduction to ammonium (DNRA), 37
 Dissolution, 4, 22–24, 57, 74, 87–90, 92–96, 98, 99, 123–125
 Dissolved organic matter (DOM), 61, 62, 66–72
 Disturbances, 25, 57, 61, 63–65, 128, 135, 151–159
 Dry deposition, 132, 149, 154
- E**
 Ecological trade-offs, 44
 Eddy covariance, 51
 Electrical conductivity, 122
 Electrical neutrality, 78, 121
 Electronegative element, 1
 Element budgets, 70, 73, 95–99
 Element cycling, 54, 95, 101, 131, 133–139, 141, 154
 Element cycling during decay, 8, 69, 70
 Element ratios, 42, 43, 65, 67
 Eluviation, 12, 22
 Emission and deposition of S and N, 36, 38, 39, 73, 74, 76
 End-member mixing analysis (EMMA), 108
 Energy budgets, 51
 Environmental controls on decay, 54, 71, 72
 Equilibrium, 3, 4, 8, 18, 20, 89, 91, 121, 124
 Equivalent weight and charge, 7
 Estimating weathering rates, 95, 96, 98–100
 Evapotranspiration, 71, 109–117, 149, 150, 158, 159
 Excess sulfate, 79
 Exchangeable acidity, 20, 21, 25
 Extractable soil aluminum, 13, 25
- F**
 Feldspars, 16, 17, 88, 90, 92, 93, 96, 102
 Fermentation, 38
 Field capacity, 16, 104, 114
 Fine roots, 24, 41, 43, 45, 52, 54, 57, 62, 64–66, 68, 72, 132, 133, 144–146
 production, 57, 145, 146
 turnover, 66, 133, 144
 Flow duration graph, 116, 117
 Flow exceedence, 116
 Flow gradient, 126
 Flow paths, 11, 101, 103, 105, 106, 108, 124, 126, 159
 Fluxes, 4, 36, 38, 39, 62, 64, 66, 72, 77, 78, 81, 83, 85, 96, 98, 99, 116, 120, 131–135, 137, 138, 142, 145, 149, 150, 152, 158
 Foliar N and photosynthesis, 48
 Forest floor, 12, 19, 61, 63, 64, 66, 109, 125, 126, 132–135, 145, 146, 154, 155, 157
 Forest floor leachates, 66, 125, 126
 Forest harvesting, 21, 87, 150, 152, 154, 159
 Forest recovery, 136, 154
 Freezing exclusion, 6
 Fulvic acids, 12, 18, 39
 Functional groups, 5, 18, 22, 54, 91
- G**
 Genesis of clays, 94
 Glacial weathering, 11, 14, 16, 92, 97, 101, 102, 104, 116, 137
 Gleyed soil, 13
 Global carbon cycle, 11, 138, 139
 Global circulation model, 138
 Global nitrogen cycle, 33, 138
 Glycolysis, 38, 50
 Gradient of stream chemistry, 96, 101, 105, 107–109, 126, 149
 Grain size distribution, 89
 Gross production, 51
 Groundwater, 23, 89, 91, 93, 101, 102, 106–110, 114, 116, 117, 122, 150
- H**
 Harvard Forest, 10, 38, 51, 63, 150, 156, 157
 Heavy metals, 1, 121
 Henry's Law, 4
 Hill reaction, 46, 47
 Hubbard Brook Forest, 63, 133, 145, 154
 Humic colloids, 17–19
 Humus, 12, 18, 20, 23, 29, 62, 67, 157
 Hydraulic conductivity, 104, 105
 Hydrogen bonding, 3
 Hydrographs, 105, 108, 110, 116, 150
 Hydrologic sources, 105, 106, 119, 120, 126, 135
 Hydrologic storage, 114, 115
 Hydrology, 101–117, 143, 150, 152, 159
 Hydrology model, 143, 150
 Hydrolysis, 34, 37, 87, 90, 96, 123, 124
 Hydrophilic, 5, 6, 121
 Hydrophobic, 5, 6, 121
 Hyetographs, 105
- I**
 Illuviation, 12, 13, 25
 Immobile plant nutrients, 56, 134
 Immobilization, 23, 31, 34, 35, 68, 69, 124–126, 132, 133, 145, 146, 150, 157
 Impaction, 57, 73–76, 81
 Infiltration, 12, 15, 19, 62, 89, 101, 104, 106, 120
 Input-output budgets, 136, 137, 152
 Interception, 57, 74, 101, 113, 114
 Interflow, 106, 108
 Ion activity, 18, 23, 90, 122, 123
 Ion exchange, 12, 17–21, 27, 29, 57, 58, 93, 121, 124–126
 Ion ratios, 22, 79
 Ionic bonds, 1, 3
 Ionic strength, 122, 123
 Isoelectric point, 17, 19, 20
 Isomorphic substitution, 17
 Isotopic dilution, 8–10, 96, 150
 Isotopic mass fractionation, 7
- K**
 Kinetic decay curve, 4
 Kinetics, 3, 4, 8, 124
 Krebs cycle, 39, 50
- L**
 Land use effects, 63, 128, 129, 150
 Land use effects on SOM, 63, 128, 129, 150
 Leachates, 66, 120, 125–127

Leaf area index (LAI), 43, 113
 Leaf longevity, 44, 45
 Leaf senescence, 65
 Ligands, 3, 19, 22, 23, 40, 90–92, 125
 Light and heavy fractions, 62
 Lignin control of decay, 52, 56, 64, 65, 67, 68, 70, 71, 148, 157
 Lithic elements, 23
 Litter decay, 68–70, 72, 145, 146
 Litterfall, 34, 54, 57, 61, 62, 64–66, 70, 72, 132–135, 144–146
 Long-range transport, 74–76, 80, 85, 144
 Lyotropic series, 19
 Lysimeters, 27, 127

M

Macronutrients, 41, 42
 Macropores, 104–107
 MAGIC model, 150
 Mass balance, 58, 66, 67, 77, 78, 83, 95, 96, 98, 99, 109, 145, 146, 150
 Mass fractionation, 8
 Measurement of deposition, 28, 34, 57–59, 73
 Measuring water budgets, 109–111
 Membrane bound calcium, 6, 59
 Mercury cycling, 40
 Mercury deposition, 31, 40, 81, 85
 Methanogenesis, 38, 39
 Methanotrophs, 39
 Methylation, 31, 40, 85
 Microbial nitrogen transformations, 32–38
 Microbial sulfur transformations, 37, 38
 Microcosms, 125, 126
 Micronutrients, 41, 42
 Micropores, 104, 107
 Mineral acids, 92
 Mineral depletion, 97, 98
 Mineral dissolution, 89, 90, 92–99, 124, 125
 Mineral stability, 90, 95
 Mineral weathering, 12, 55, 87–99, 120, 124–126, 132, 134, 135, 137, 150
 Mineralization, 31, 34–38, 55, 61, 67–71, 120, 125, 126, 131–135, 145, 146, 149, 150, 153, 157
 Mineralogical controls, 90
 Mineralogy, 16, 90, 94, 104
 Mobile anions, 23, 28, 35, 120, 126, 134
 Mobile plant nutrients, 56, 76
 Models, 10, 14, 42, 66, 84, 106, 108, 111, 121, 136, 141, 152
 Models of atmospheric deposition, 20, 23, 28, 34, 40, 54, 55, 58, 61, 73–85, 97, 99, 132–137, 149, 157
 Monthly precipitation chemistry, 109, 112, 148
 Montmorillonite, 17, 95
 Mycorrhizae, 45, 55, 93

N

Necromass, 57, 61
 Net ecosystem production (NEP), 51
 Nitrate reduction, 36, 37
 NITREX study, 157
 Nitrification, 35, 36, 72, 120, 124, 125, 133, 145, 150, 153, 154, 157
 Nitrogen cycling model, 133, 138, 144–146
 Nitrogen fixation, 32, 34
 Nitrogen immobilization, 34, 35
 Nitrogen loading, 154, 156
 Nitrogen oxides (NO_x), 74, 76, 79, 80
 Nitrogen saturation, 144, 155
 Nutrient use efficiency (NUE), 58

Nutrients, 11, 16, 17, 20, 21, 23, 27, 29, 41–43, 46–48, 52, 54–59, 63–65, 67, 69, 70, 87, 88, 93, 116, 125, 131, 134–136, 141, 147, 148, 150, 152–156, 159
 cycling and succession, 43, 45, 54, 57, 58, 61, 69, 88, 101, 125, 131, 135–137, 141, 152, 154, 155
 limitation, 46, 58
 in litterfall and leaching, 136, 150, 155
 requirement, 132
 uptake, 16, 23, 45, 52, 54–56, 131, 147

O

Octahedron, 17
 Operational definitions, 6, 121
 Optimal plant nutrition, 16, 43, 46, 58, 72, 104
 Organic acids, 5, 12, 18, 21–23, 39, 40, 49, 91–93, 125, 126
 Organic chemistry, 4, 5
 Organic matter budgets, 61, 62, 64, 66, 72
 Organic sulfur mineralization, 37
 Orographic precipitation, 84, 111
 Osmotic potential, 6, 48
 Ozone, 36, 59, 60, 76, 80, 147
 Ozone stress, 59, 60

P

Parent materials, 11–14, 16, 24, 97, 136
 Peak flows, 108, 116, 150
 Pedogenesis, 11, 12
 Periodic table, 1
 Phenology, 52, 113
 Photosynthesis, 9, 43–46, 48–52, 60, 138, 147, 149
 Photosynthetic active radiation (PAR), 49
 Piston flow displacement, 106, 107
 Plant canopy, 43, 44, 57, 58, 81, 125
 Plant chemistry, 41–43
 Plant defensive chemistry, 52, 53
 Plant growth allocation, 34, 41, 43, 48, 49, 58
 Plant nutrient absorption, 54–56
 Plant nutrient cycling, 54–58
 Plant stress, 159
 PnET model, 149, 150
 Podzolization, 12, 25
 Polarity, 5, 6
 Pools, 4, 8, 25, 27, 34, 36, 41, 42, 45, 52, 55, 61–63, 71, 72, 88, 95, 98, 99, 104, 114, 119, 131–135, 138, 139, 144–148, 150, 154, 156, 158, 159
 Precipitation, 8, 11, 57, 62, 74, 88, 101, 119, 148, 159
 chemistry, 78–85
 reactions, 23, 24, 120, 125, 126
 Preferential dissolution, 89
 Preferred pathways, 105
 Prescribed burning, 152, 154, 155
 Primary minerals, 17, 23, 87, 88, 95–99
 Primary production, 44, 46, 51, 60–62, 65, 132, 144–147, 154
 Problem sets, 8
 Production efficiency, 51

Q

Quickflow, 106, 107, 116

R

Raleigh distillation coefficient, 8
 Rate limitation, 4, 89, 124

- Reaction rates, 4, 10, 72, 91, 123
 Redox conditions, 31, 32, 123
 Residence time, 4, 25, 45, 61, 63, 68, 74, 75, 101
 Residence time of soil carbon, 4, 25, 45, 61, 68, 74, 75, 101
 Resorption, 56, 57, 66, 132–134, 144–146
 Respiration, 12, 31, 38, 39, 50, 51, 53, 54, 59, 61, 72, 91, 125, 138, 141, 147, 148
 Retranslocation, 56
 Rhizosphere, 22–24, 33, 35, 43, 45, 54, 89, 93
 Riparian zones, 31, 106
 River discharge, 110, 122
 River exports, 99, 101, 108, 110, 115, 116, 128, 137
 Root biomass, 57, 58, 64, 65, 72, 149
 Root:shoot ratio, 46
 Root system, 43, 45, 52, 54, 57, 62, 132
 Root turnover, 61, 65, 66, 132–135, 144–146
 Rubisco, 48
 Runoff, 27, 72, 89, 96, 99, 101, 105–109, 115–117, 128, 132, 137, 138, 143, 150, 154, 159
- S**
- Salicylic acid, 3, 5, 92
 Sapwood area, 44
 Saturated zones, 105, 106
 Saturation index, 23
 Sea salt correction, 74
 Seasonal rainfall, 112
 Secondary compounds, 52
 Secondary minerals, 16, 17, 87, 88, 95, 96, 99
 Senescence, 56, 57, 59, 65, 66, 147
 Sensitivity analysis, 143, 144, 146
 SI units and concentrations, 7
 Silica polymerization, 87, 90, 93, 95, 96, 98, 99
 Sinks, 10, 11, 23, 31, 36, 37, 39, 43, 52, 54, 56, 69, 70, 73, 119, 120, 128, 131, 133, 135–137, 139, 145, 146, 151–157, 159
 Snowmelt, 6, 23, 93, 105–109, 114–117
 Snowpack, 101, 109, 114, 117, 150, 159
 Soil acidification, 21, 87, 154, 156, 157
 Soil aluminum, 13, 25
 Soil buffer capacity, 22
 Soil carbon, 62, 63, 71
 Soil chemical properties, 24, 25, 27, 28
 Soil classification, 13, 14
 Soil colloids, 15, 17–19, 23, 54, 94, 104, 125
 Soil exchange chemistry, 24, 25
 Soil formation, 11–14, 23, 97
 Soil heavy and light fractions, 158
 Soil horizons, 12, 13, 18, 20–25, 27, 62, 63, 104, 106–108, 145, 147, 159
 Soil hydraulic conductivity, 104
 Soil hydrology, 104–106
 Soil leaching, 12, 23, 131, 132, 155, 156
 Soil mineralogy, 16, 94
 Soil moisture, 12, 15, 16, 48, 91, 101, 107, 109, 110, 113, 114, 154
 Soil nitrogen, 55, 154
 Soil nutrient supply and storage, 21, 27, 55, 154, 159
 Soil orders, 13, 14
 Soil organic carbon (SOC), 25, 62, 158
 Soil organic matter (SOM), 9, 10, 14, 24, 34, 61–64, 67, 71, 131–133, 145, 148–150, 157, 158
 Soil profiles, 9, 11–16, 20, 22–25, 27, 34, 45, 62, 64, 66, 87, 89, 93, 95–98, 104, 108, 120, 126, 128, 134
 Soil respiration, 72, 125
 Soil solution chemistry, 18, 27, 28, 93, 94, 119–121, 152
 Soil texture, 13–15, 34, 62, 104, 148
 Soil water, 48, 91, 94, 104, 108, 114, 120, 124, 127, 142, 146, 159
 Solubility, 3–6, 22, 23, 90, 91, 123
 Solution chemistry, 12, 18, 27, 28, 58, 93, 94, 108, 119–121, 124–128, 152
 SOM turnover rate, 159
 Spatial patterns of deposition, 81, 82
 Stable isotopes, 4, 7–10, 34
 State variables, 142, 144, 147
 Steady state, 4, 46
 Steady-state, 98, 106, 136, 150
 Stemflow, 57, 77, 132, 133
 Stoichiometry, 3, 4, 43, 90, 93, 96, 159
 Stomatal conductance, 49, 50, 59, 113
 Stream chemistry, 96, 101, 105, 107–109, 126–128, 149
 Stream gauge, 110
 Stream order, 101
 Stream runoff, 10, 27, 89, 99, 101, 106, 108, 109, 116, 117, 120, 128, 129, 132, 133, 135, 136, 143, 150, 154, 156
 Streamflow generation, 105–109
 Stresses, 16, 21, 41, 49, 52, 58–60, 80, 109, 115, 147, 151, 152, 155, 157, 159
 Strong acids, 21–23, 79, 81, 84, 91, 92, 99, 121, 126, 128, 137
 Substrate controls on decomposition, 70, 71
 Succession, 21, 33, 34, 62, 64, 65, 106, 113, 128, 136, 150, 151, 153, 159
 Sulfate adsorption, 19, 20, 27, 120, 126, 127, 137, 149, 154
 Sulfate reduction, 24, 38, 40, 125
 Sulfur oxide (SO_x), 76
 Surficial geology, 101–103
- T**
- Tannins, 52, 53
 TEM model, 148
 Temperature effects, 72
 Tetrahedron, 17, 90
 Trace metals, 1, 23, 33, 43, 87
 Tracers of weathering, 10, 34, 77, 96–98, 107, 108
 Transpiration rates, 110, 113
 TREGRO model, 52, 147
- U**
- Unsaturated zone, 105
- V**
- Validation of a model, 142, 143
 Vapor pressure deficit (VPD), 49, 50, 112, 113, 142
 Variable source area, 106, 107
 Vermiculite, 17, 95, 99
 Volume-weighted mean, 84
- W**
- Water analysis, 3–6, 8, 12, 28, 41, 43, 46, 49, 66, 77, 78
 Water balance, 108–117
 Water budgets, 108–117, 148, 150, 153
 Water chemistry and mineral dissolution, 13, 27, 79, 84, 93, 105, 124, 150, 152
 Water potentials, 48, 49, 112, 113, 142, 147
 Water sample collection, 6, 7, 12, 27, 78, 121, 122, 124
 Water table, 39, 105, 106, 159
 Watershed acidification model, 149, 150
 Watershed hydrology, 101–117, 143, 150
 Weak acids, 5, 23, 90–92, 122

-
- Weathering estimates, 95, 98
 - Weathering export fluxes, 99
 - Weathering processes, 21, 87–89, 94, 96, 97, 100
 - Weathering rates, 89–93, 95, 96, 98–100
 - Weathering reactions, 88, 90, 91, 93–97
 - Weathering solutions, 91, 93
 - Wet deposition, 57, 58, 73, 74, 77–79, 81–83, 85, 109, 125, 137
 - White rots, 67, 68
 - Wildfire, 152, 154, 155, 159
 - Wilting point, 16, 104
 - Wood decay, 67, 68
- Z**
- Zero point of charge (ZPC), 19