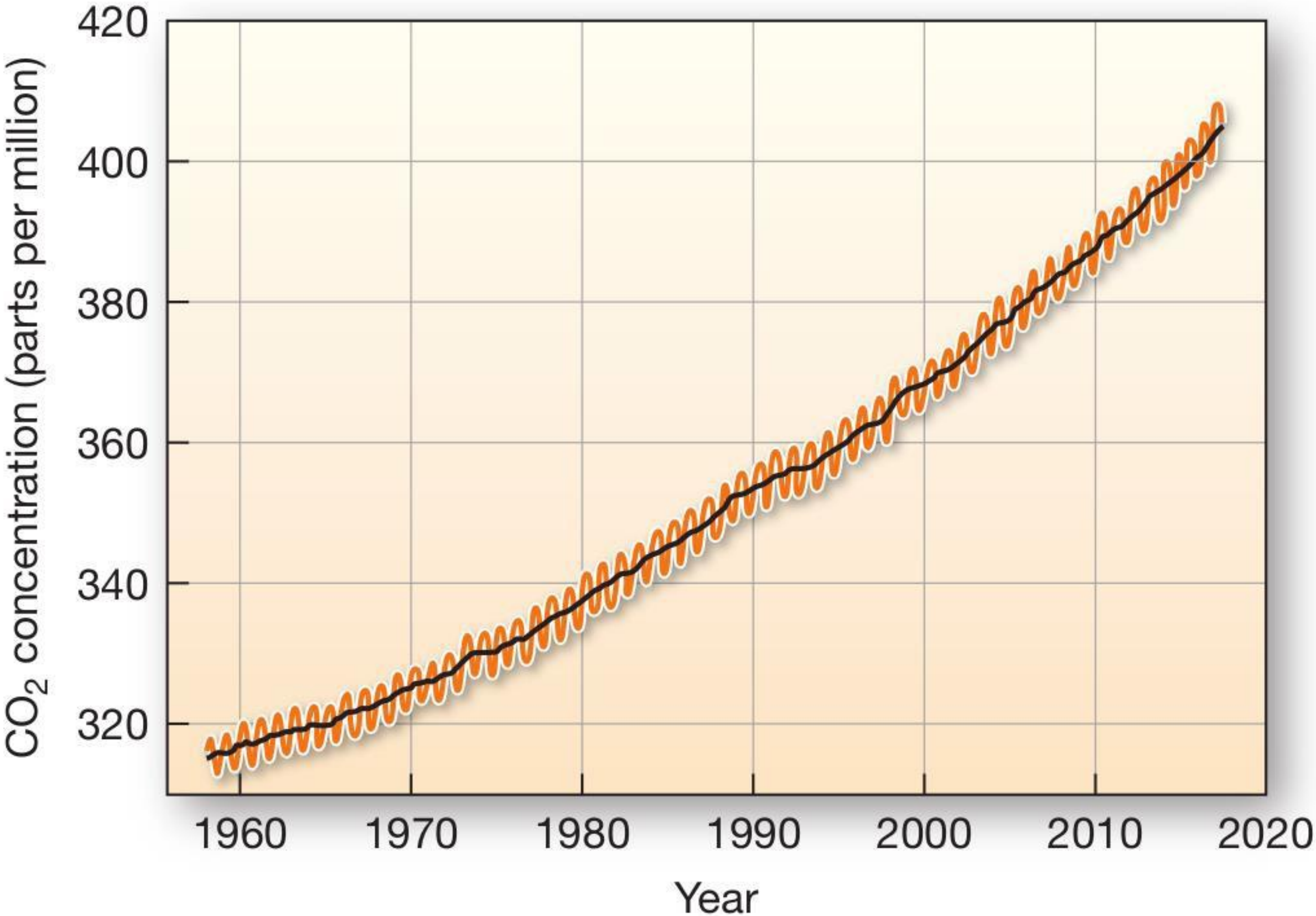
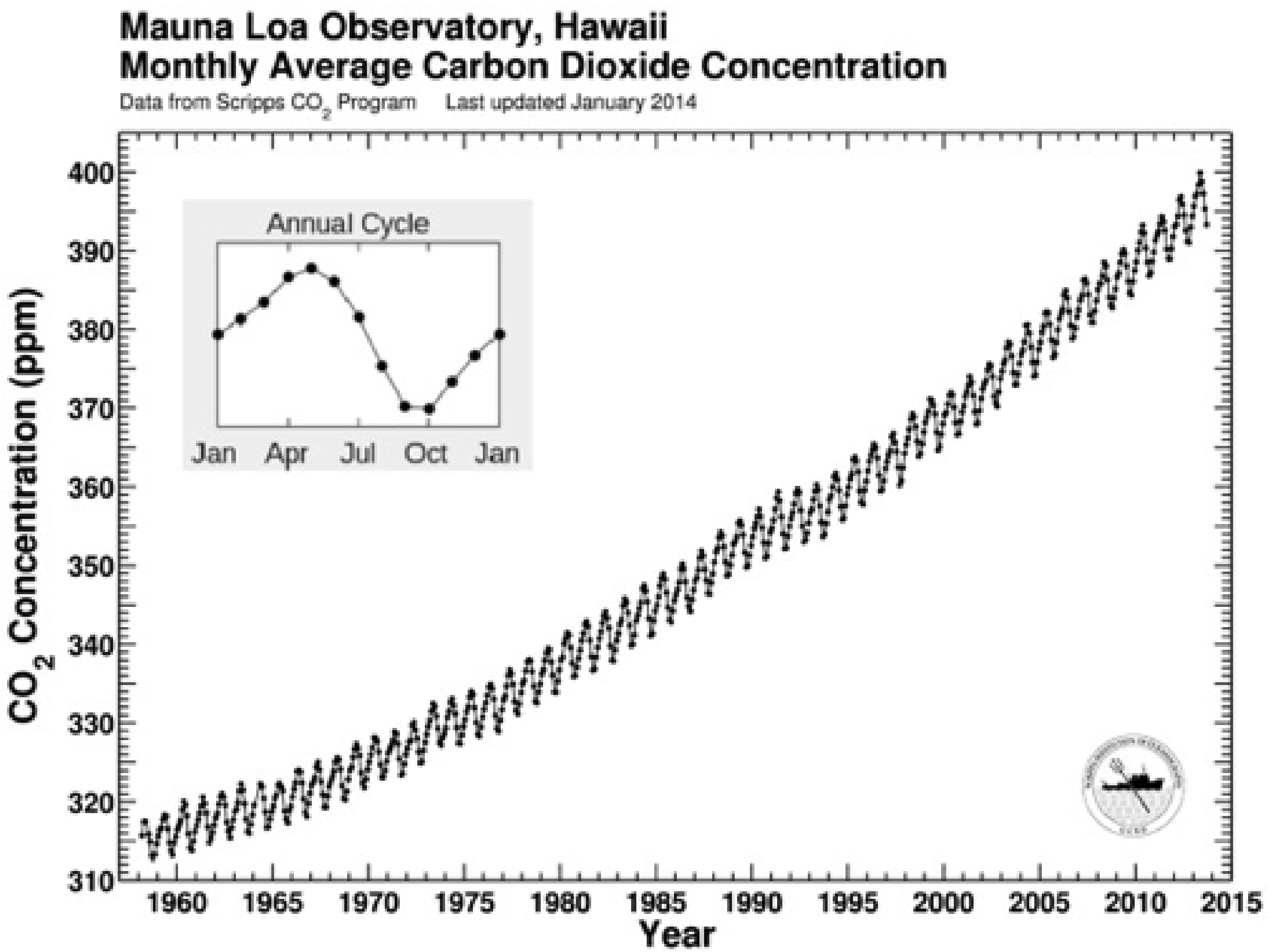

420
400
380
360
340
320
CO_2 concentration (parts per million)
1960
1970
1980
1990
2000
2010
2020
Year

Figure 2.19


Mauna Loa Observatory, Hawaii
Monthly Average Carbon Dioxide Concentration
Data from Scripps CO_2 Program Last updated January 2014
Annual Cycle
Jan Apr Jul Oct Jan
CO_2 Concentration (ppm)
400
390
380
370
360
350
340
330
320
310
1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015
Year

ESS 411: Earth Systems Ecology

Fall 2025

Class Times & Location: Tuesday, Thursday 11:00-12:15 pm in Clark Building, Room C 337

Instructor: Dr. John Moore
Office: Natural and Environmental Science Building B227
Email: John.moore@colostate.edu
Office Hours: Mondays 10 -11 am

Teaching Assistant: April Johns
Office: Natural and Environmental Science Building A229
Email: april.johns@colostate.edu

Office Hours: Wednesday 10-11am

Prerequisites: ESS 311 & 312

Required Text: ***Biogeochemistry, An Analysis of Global Change*** (3rd edition) by William Schlesinger and Emily Bernhardt, Academic Press, 2013.

Attendance and Class Participation: You are responsible for attending all classes. Lecture slides will be posted on canvas.

Assignments: All assignments are due by 11:59 pm on the due date specified. Late assignments will receive a 10% per day penalty after the deadline.

Grading: Your grade will be based on your performance on exams, assignments, and reflections. The total course grade is distributed between the following categories:

Weekly Reflections:	150 pts (15 @ 10 pts each)
Assignments:	200 pts (4 @ 50 pts each)
Portfolio:	100 pts
Exams:	350 pts (Exams 1&2 @ 100 pts each; Final @ 150 pts)

Canvas: You are expected to have access to and regularly log in to Canvas (http://info.canvas.colostate.edu/login.aspx). Important class information will be posted, and assignments will be submitted there. Grades are also posted on Canvas. Note that posted grades will stand and any class-wide adjustments to final course scores are at the discretion of the instructor. The standard plus/minus system is used: A+, A, A-, B+, B, B-, C+, C, D, F.

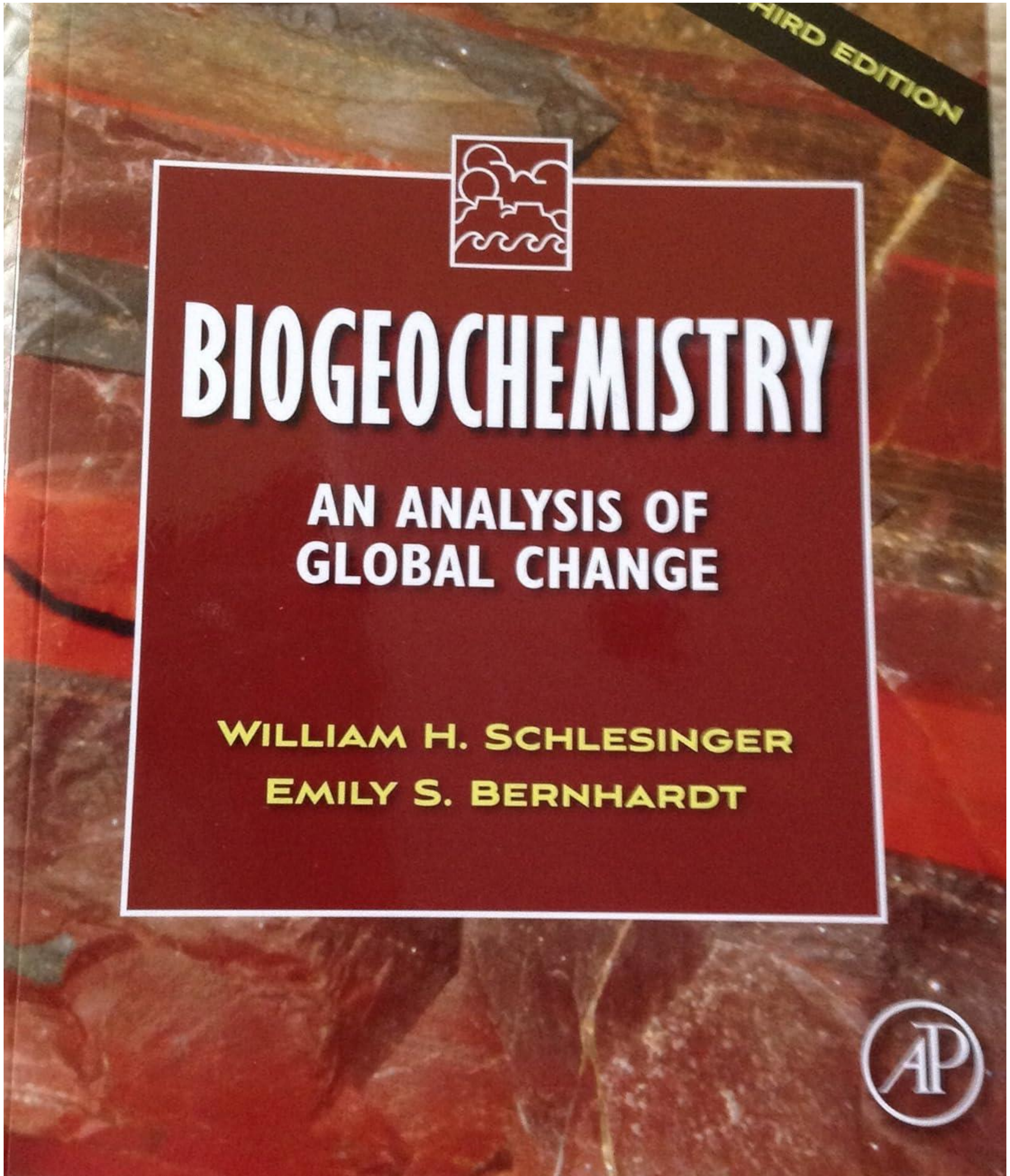
Learning Objectives

Course Overview: Earth Systems students will assess how human activity is altering the energy and material flows through both the living (plants, animals, microbes) and non-living (soils, atmosphere) components of ecological systems. Our goal is to develop a solid **understanding of** the links between **ecosystem function and biogeochemistry**, and examine how **global change** factors affect these links.

The course aims to provide students with:

- an understanding of how global change is altering Earth systems' structure and function around the world, with an emphasis on biogeochemistry
- a basis in the scientific theory of global change biology and thresholds
- familiarity with scientific methods used to study ecosystems and biogeochemistry, with an emphasis on use of stable and radio isotopes
- experience preparing and writing a formal grant proposal
- proficiency in science writing, with awareness of issues around bias in Earth systems research and writing

Chapter 1 Lecture



Elemental Geosystems

Earth systems and human-Earth connections

- PART 1 Energy-Atmosphere System
  - Gases and particulates make up the air we breathe and filter the Sun's harmful radiation. Energy from the Sun drives atmospheric circulation.
- PART 2 Water, Weather, and Climate Systems
  - Water in the atmosphere and on Earth's surface affects weather and climate. Water availability is critical for humans and other organisms.
- PART 3 Earth-Atmosphere Interface
  - Forces within Earth build and warp crustal landforms at the same time that processes on Earth's surface wear landforms away
- PART 4 Soils, Ecosystems, and Biomes
  - Solar energy powers the biosphere as plants and algae convert sunlight into food. Soils are the medium for plant growth.

Earth as a System and its Four Spheres

- Earth is too complex to permit a single model to represent the whole planet . System- a set of components that are interrelated. We divide Earth into abiotic (non-living) and biotic (living) spheres.
- Three abiotic spheres: atmosphere, hydrosphere, lithosphere (geosphere); and one biotic sphere: biosphere,

A. **Atmosphere:** Gaseous envelope surrounding Earth.

B. **Hydrosphere:** Water, including ice (cryosphere)

C. **Lithosphere:** Solid part of the Earth (rocks, minerals, soil)

D. **Biosphere:** The living portion of the Earth, made possible by the other three.

Week	Dates	Topics (Subject to Change)
1	T 8/26 R 8/28	Course Overview Introduction to Biogeochemistry – *Chapter 1* ***Reflection 1 - Due***
2	T 9/2 R 9/4	Origins – *Chapter 2* *Assignment 1* ***Reflection 2 - Due***
3	T 9/9 R 9/11	The Atmosphere – *Chapter 3* ***Reflection 3 - Due***
4	T 9/16 R 9/18	The Lithosphere - *Chapter 4* ***Reflection 4 - Due*** ***Assignment 1 - Due***
5	T 9/23	Review and Discussion *Assignment 2 - Assigned Reading – Literature Review and Reverse Outlines*
	R 9/25	**Exam 1** ***Reflection 5 - Due***
6	T 9/30 R 10/2	The Biosphere: The Carbon Cycle of Terrestrial Ecosystems - *Chapter 5* ***Reflection 6 - Due***
7	T 10/7 R 10/9	The Biosphere: Biogeochemical Cycling on Land – *Chapter 6* ***Assignment 2 - Due*** ***Reflection 7 – Due***
8	T 10/14 R 10/17	Wetland Ecosystems – *Chapter 7* *Assignment 3 – Logic Model and Proposal Outline* ***Reflection 8 - Due***
9	T 10/21 R 10/23	Inland Waters – *Chapter 8* ***Reflection 9 - Due***

10	T 10/28 R 10/30	The Oceans - *Chapter 9* ***Reflection 10 - Due***
11	T 11/4 R 11/6	Review and Discussion **Exam 2** ***Reflection 11 - Due***
12	T 11/11 R 11/13	The Global Water Cycle – *Chapter 10* ***Assignment 3 Due*** ***Reflection 12***
13	T 11/18 R 11/20	The Global Carbon Cycle – *Chapter 11* *Assignment 4 – Final Proposal* ***Reflection 13 - Due***
Fall Break	T 11/25 R 11/27	**Fall Break/University Holiday- No Classes**
14	T 12/2 R 12/4	The Global Cycles of Nitrogen and Phosphorus – *Chapter 12* The Global Cycles of Sulfur and Mercury – *Chapter 13* ***Reflection 14 - Due***
15	T 12/9 R 12/11	Perspectives – *Chapter 14* Review and Discussion ***Assignment 4 - Final Proposal Due*** ***Portfolio - Due*** ***Reflection 15 – Due***
Finals Week	W 12/17	**Final Exam - Thursday, December 18th, 6:20 – 8:00 pm**

Grading System

Grading (Traditional Letter Grade) based on score out of 800 total points:

- **Weekly Reflections (150 points: 15 @ 10 points each)**
  All weekly reflections will be submitted via canvas (10 points each). Each week, you will be asked to write a short (3-5 sentences) reflection on the concepts we cover during that week. The goal is to give you an opportunity to reflect on your own learning and progress throughout the course. Consider the following questions when writing up your weekly reflections (you do not need to answer all each week; you are also not limited to writing on only these topics):
    - What was the most important/interesting thing you learned this week?
    - Do you have any questions or confusions about the course material for the week?
    - How do the concepts we covered this week relate to your other courses or experiences?
- **Assignments (200 points: 4 @ 50 points each)**
  All assignments will be submitted via canvas. Please put your name, the class, date, semester, and assignment number on each assignment.
    - Assignment 1 (50 points) – Assigned Reading – CV, Career Statement, Readings, & Reverse Outline
    - Assignment 2: (50 points) – Assigned Reading – Literature Review and Reverse Outlines
    - Assignment 3: (50 points) – Proposal Outline
    - Assignment 4: (50 points) – Final Proposal
- **Exams (200 points: 2 @ 100 points each)**
  There will be two in-class exams. Test format will include multiple choice, true/false, matching questions and short/long answer questions. The exams will contain recently covered.
- **Portfolio (100 points)**
  Compilation of course materials (lectures and readings), notes, and assignments.
- **Final Exam (150 points)**
  In class, comprehensive, written exam

Weekly Reflections

Write a short (3-5 sentence) reflection on the concepts we covered this week. The goal is to give you an opportunity to reflect on your own learning and progress throughout the course.

For Week 1 provide a summary of your career goals and why you chose your major.

Consider the following questions when writing your reflection (you do not need to answer all each week; you are also not limited to writing on only these topics):

- What was the most important/interesting thing you learned this week?
- Do you have any questions or confusions about the course material for the week?
- How do the concepts we covered this week relate to your other courses or experiences?

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    - Assignment 3: (50 points) – Proposal Outline
    - Assignment 4: (50 points) – Final Proposal

NSF 24-591: NSF Graduate Research Fellowship Program (GRFP)

Program Solicitation

Document Information

Document History
- **Posted:** July 12, 2024
- **Replaces:** NSF 23-605

Grading System

Grading (Traditional Letter Grade) based on score out of 800 total points:

- **Weekly Reflections (150 points: 15 @ 10 points each)**
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- **Portfolio (100 points)**
  Compilation of course materials (lectures and readings), notes, and assignments.
- **Final Exam (150 points)**
  In class, comprehensive, written exam

CHAPTER

1

Introduction

OUTLINE

WHAT IS BIOGEOCHEMISTRY?

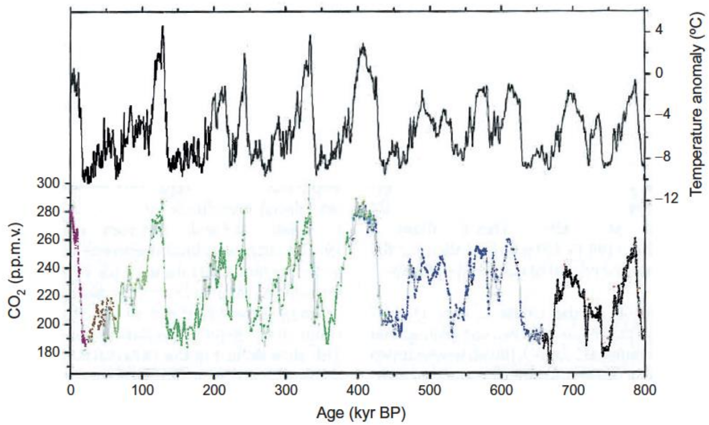


FIGURE 1.2 An 800,000-year record of CO_2 and temperature, showing the minimum temperatures correspond to minimum CO_2 concentrations seen in cycles of ~120,000 periodicity, associated with Pleistocene glacial epochs. *Source: From Luthi et al. (2008)*

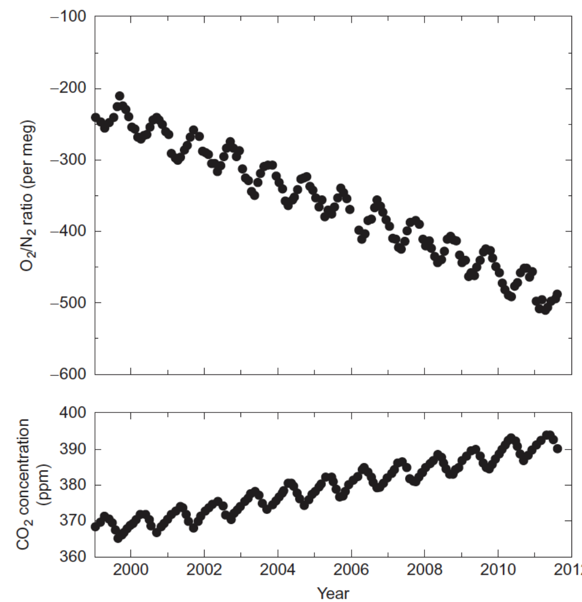
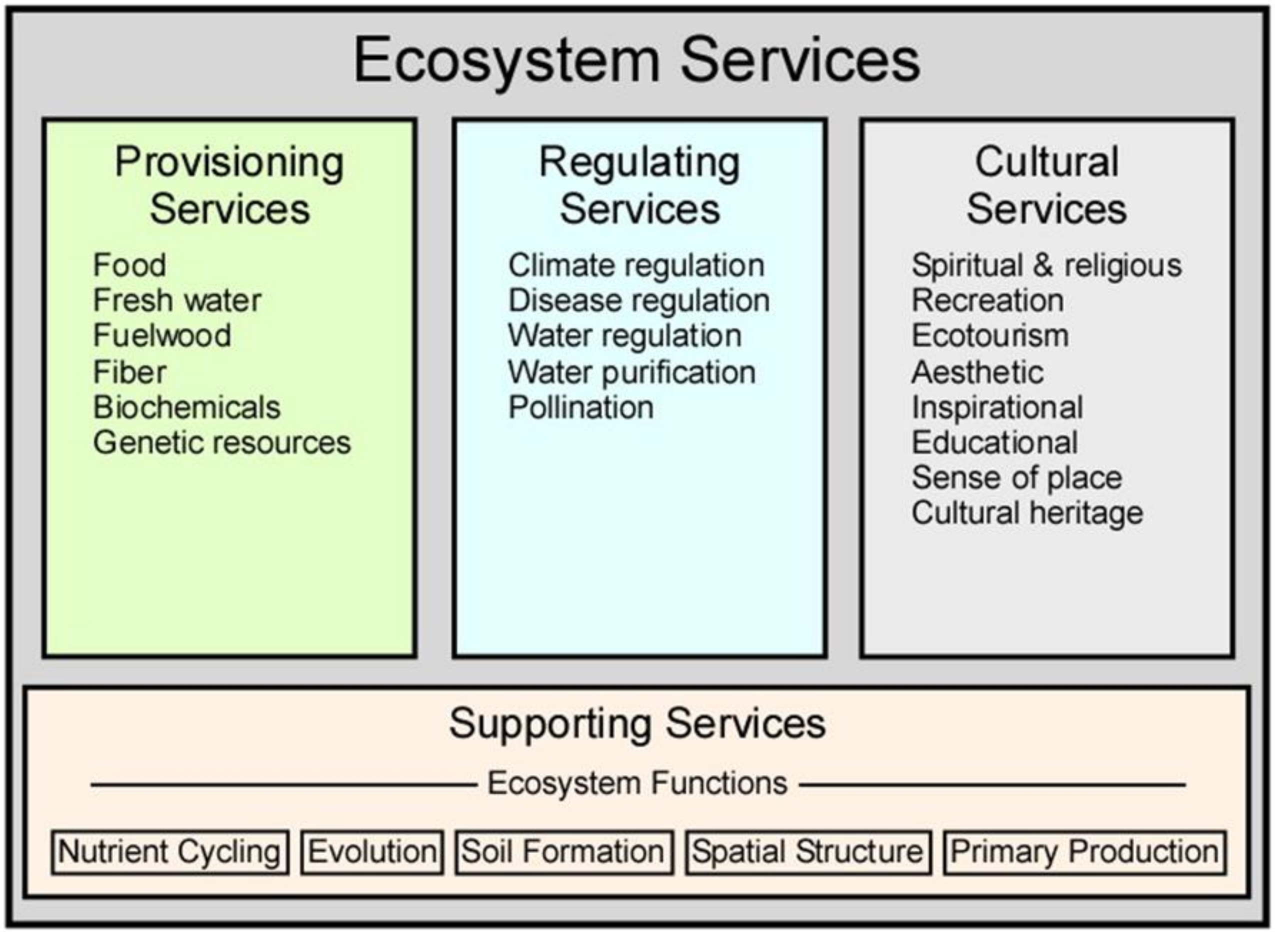
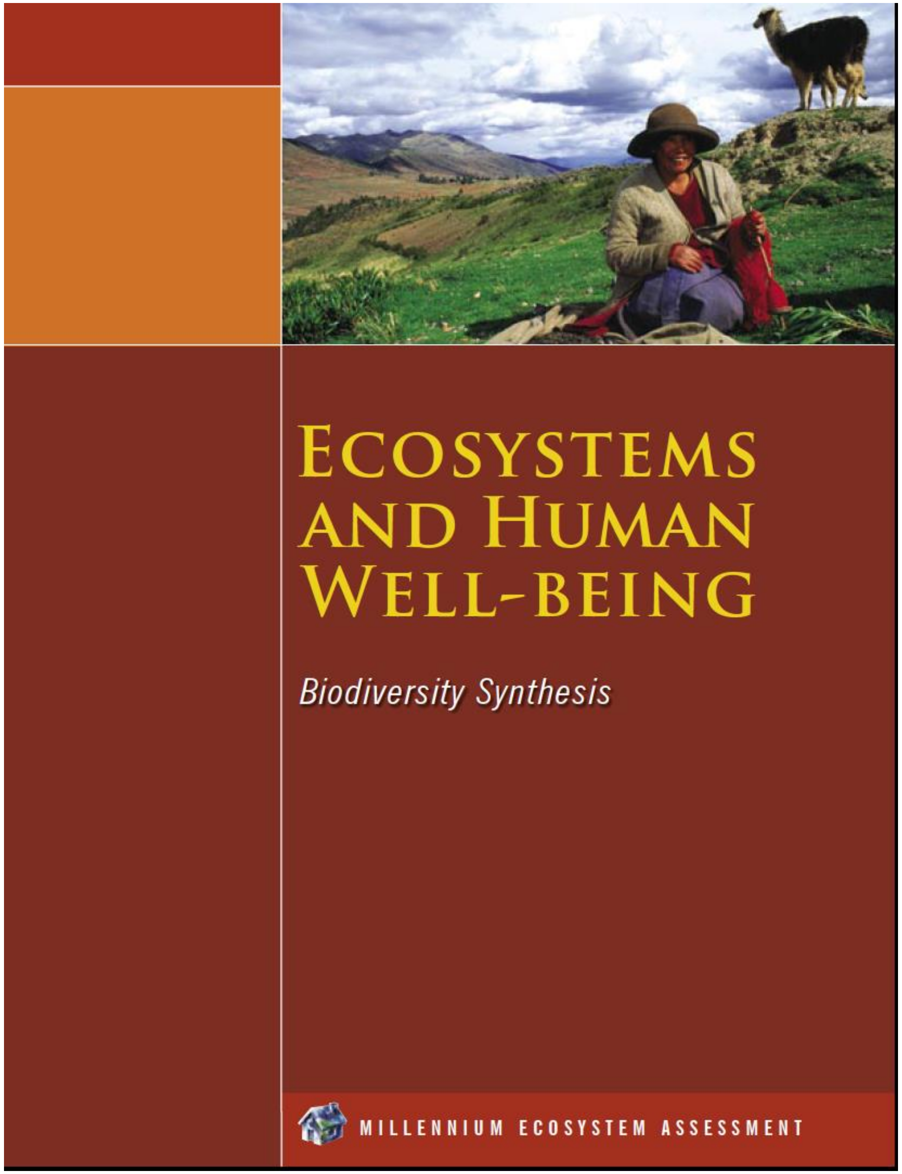


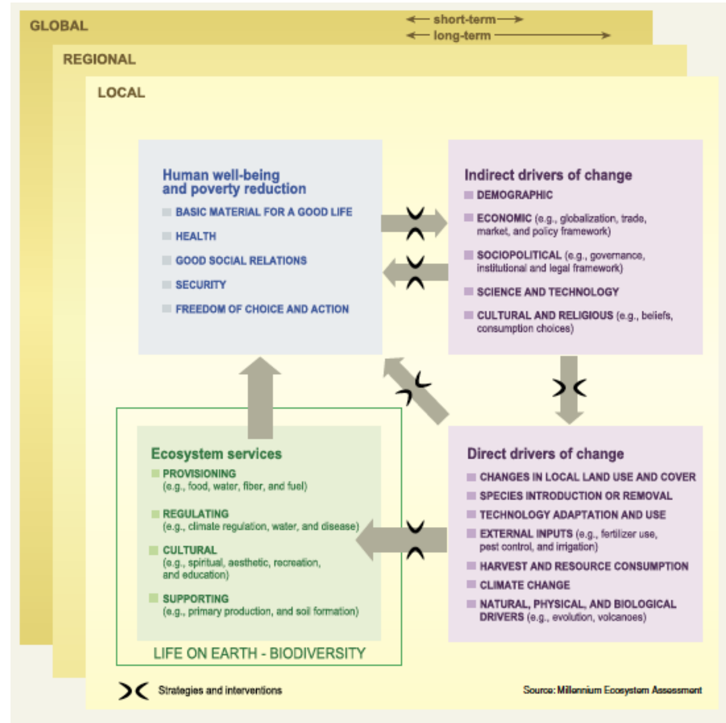
FIGURE 1.1 Annual cycles of CO_2 and O_2 in the atmosphere. Changes in the concentration of O_2 are expressed relative to concentrations of nitrogen (N_2) in the same samples. Note that the peak of O_2 in the atmosphere corresponds to the minimum CO_2 in late summer, presumably due to the seasonal course of photosynthesis in the Northern Hemisphere. *Source: From Ralph Keeling, unpublished data used by permission.*



Modified, with additions, from the Millennium Assessment



Framework of Interactions between Biodiversity, Ecosystem Services, Human Well-being, and Drivers

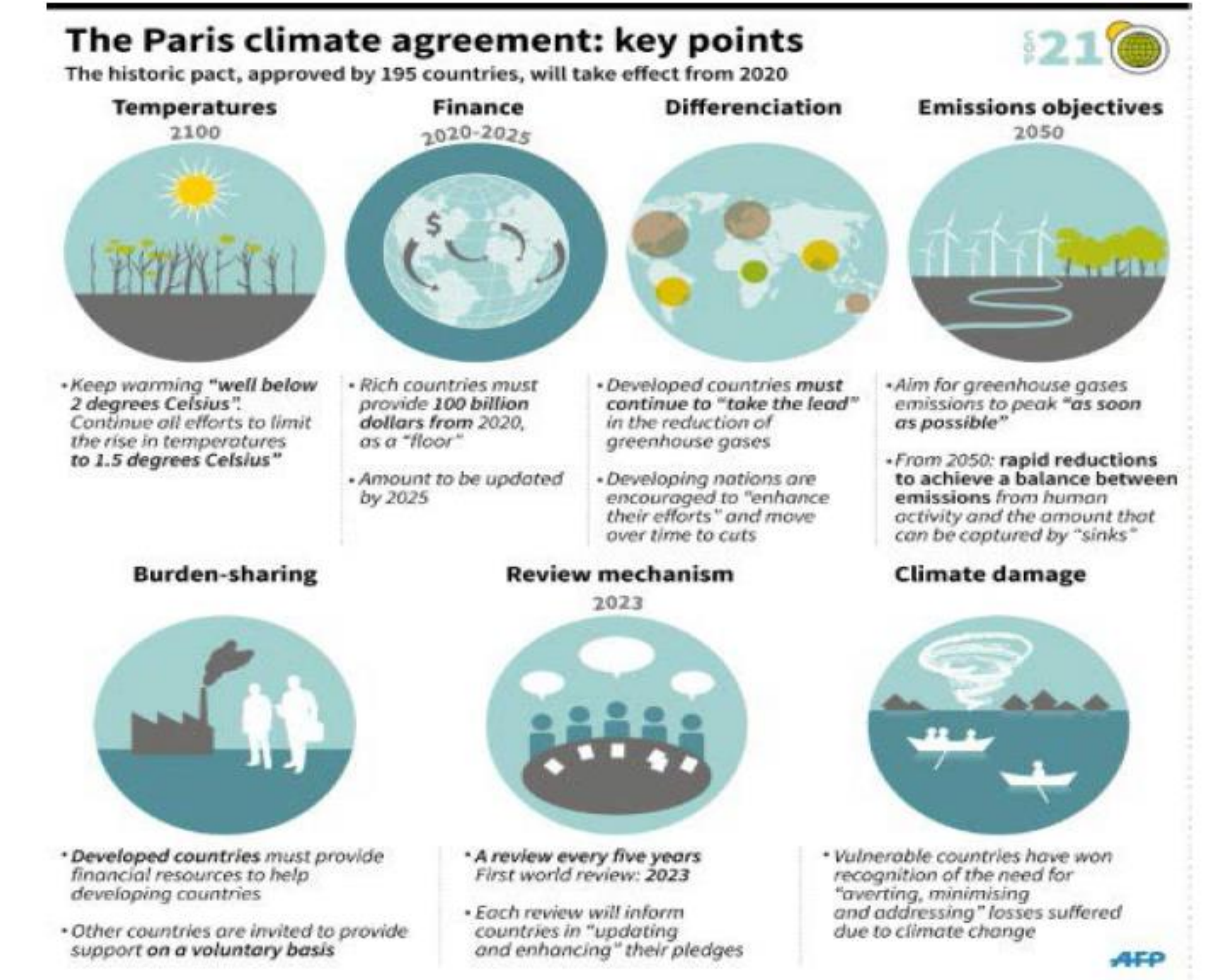


Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Biodiversity Synthesis.* World Resources Institute, Washington, DC.

Library of Congress Cataloging-in-Publication data.

The IPCC's Sixth Assessment Report (AR6)1 on the physical science basis of climate change

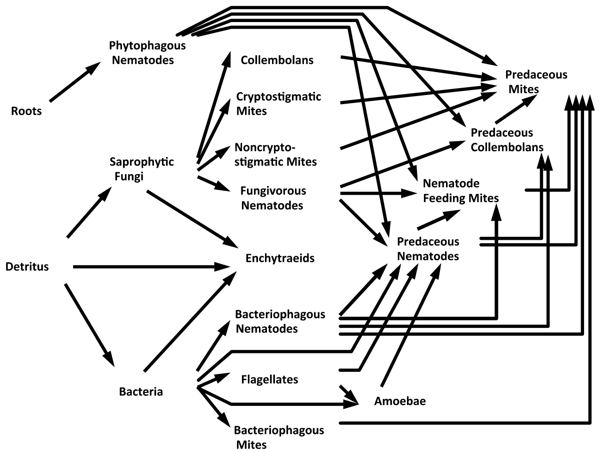
Provides a high-level summary of the understanding of the current state of the climate, including how it is changing and the role of human influence, the state of knowledge about possible climate futures, climate information relevant to regions and sectors, and limiting human-induced climate change.


The Paris climate agreement: key points
The historic pact, approved by 195 countries, will take effect from 2020
COP21
Temperatures
2100
• Keep warming "well below 2 degrees Celsius". Continue all efforts to limit the rise in temperatures to 1.5 degrees Celsius"
Finance
2020-2025
$
• Rich countries must provide 100 billion dollars from 2020, as a "floor"
• Amount to be updated by 2025
Differenciation
• Developed countries must continue to "take the lead" in the reduction of greenhouse gases
• Developing nations are encouraged to "enhance their efforts" and move over time to cuts
Emissions objectives
2050
• Aim for greenhouse gases emissions to peak "as soon as possible"
• From 2050: rapid reductions to achieve a balance between emissions from human activity and the amount that can be captured by "sinks"
Burden-sharing
• Developed countries must provide financial resources to help developing countries
• Other countries are invited to provide support on a voluntary basis
Review mechanism
2023
• A review every five years First world review: 2023
• Each review will inform countries in "updating and enhancing" their pledges
Climate damage
• Vulnerable countries have won recognition of the need for "averting, minimising and addressing" losses suffered due to climate change
AFP

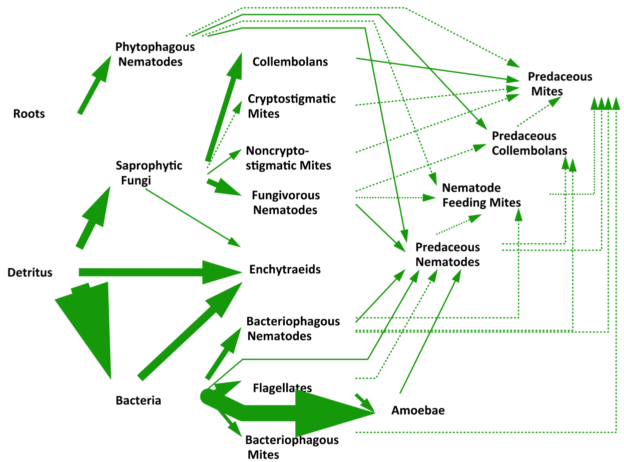
Sustainable Development Goals

System Characteristics
Entities and Components

Structure



Function

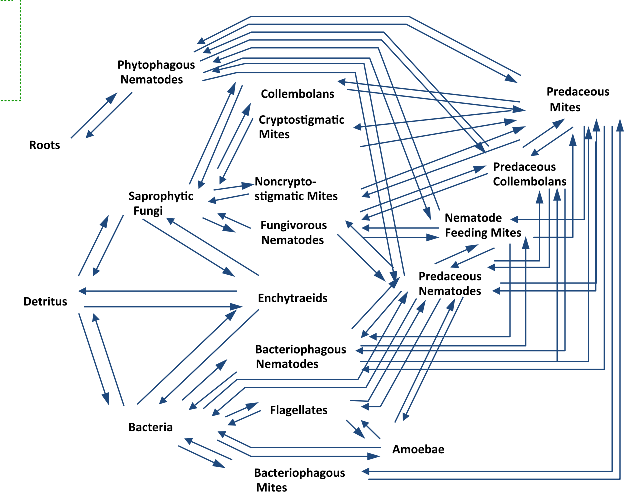


Structure

Function

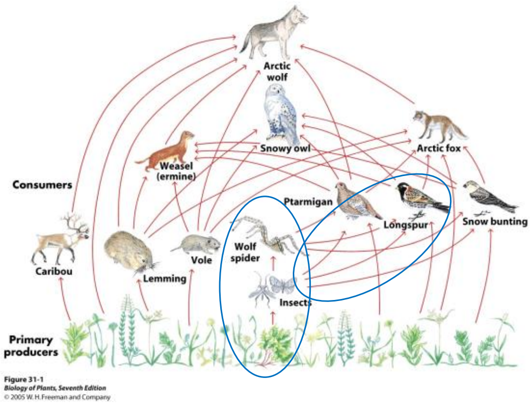
Behavior

Behavior



The topics are organized as dynamic hierarchical systems

Level	*Dominant Principle(s)*
Molecular/Cellular	Genetics and Evolution
Individual/Species	Genetics and Evolution/Thermodynamics
Population/Species	Genetics and Evolution/Thermodynamics
Community/Multiple Species	Thermodynamics/Systems Theory
Ecosystem	Thermodynamics/Systems Theory

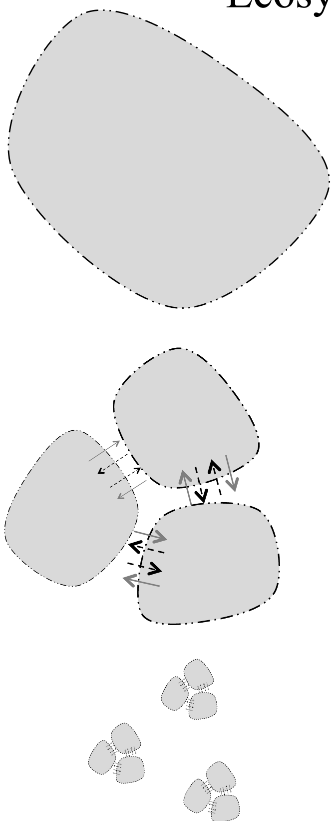


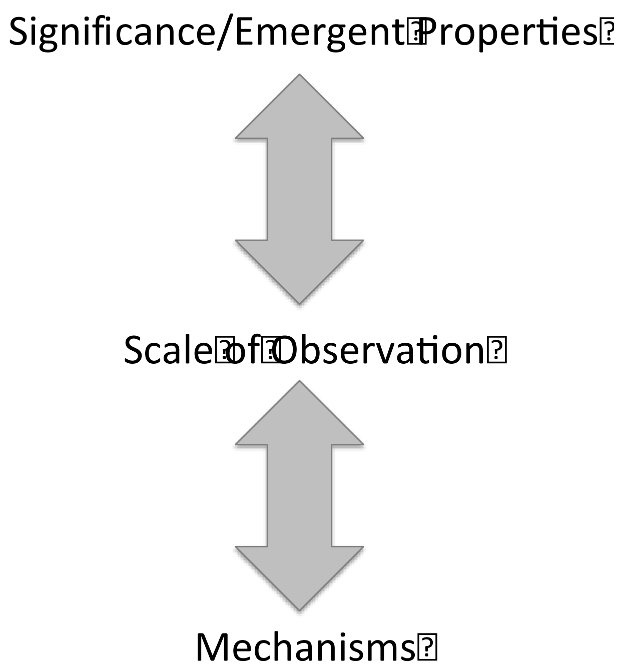
The topics include multiple principles operating simultaneous

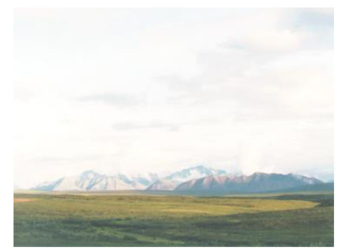
Level	*Dominant Principle(s)*
Molecular/Cellular	Genetics and Evolution
Individual/Species	Genetics and Evolution/Thermodynamics
Population/Species	Genetics and Evolution/Thermodynamics
Community/Multiple Species	Thermodynamics/Systems Theory
Ecosystem	Thermodynamics/Systems Theory

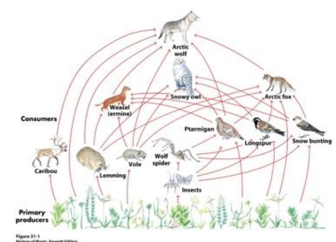
The importance of the principles changes as one moves up and down the hierarchy.

Level	*Dominant Principle(s)*
Molecular/Cellular	Genetics and Evolution
Individual/Species	Genetics and Evolution/Thermodynamics
Population/Species	Genetics and Evolution/Thermodynamics
Community/Multiple Species	Thermodynamics/Systems Theory
Ecosystem	Thermodynamics/Systems Theory









There are pivotal nodes, levels, or scales within the hierarchy that serve as an entry points to the system.

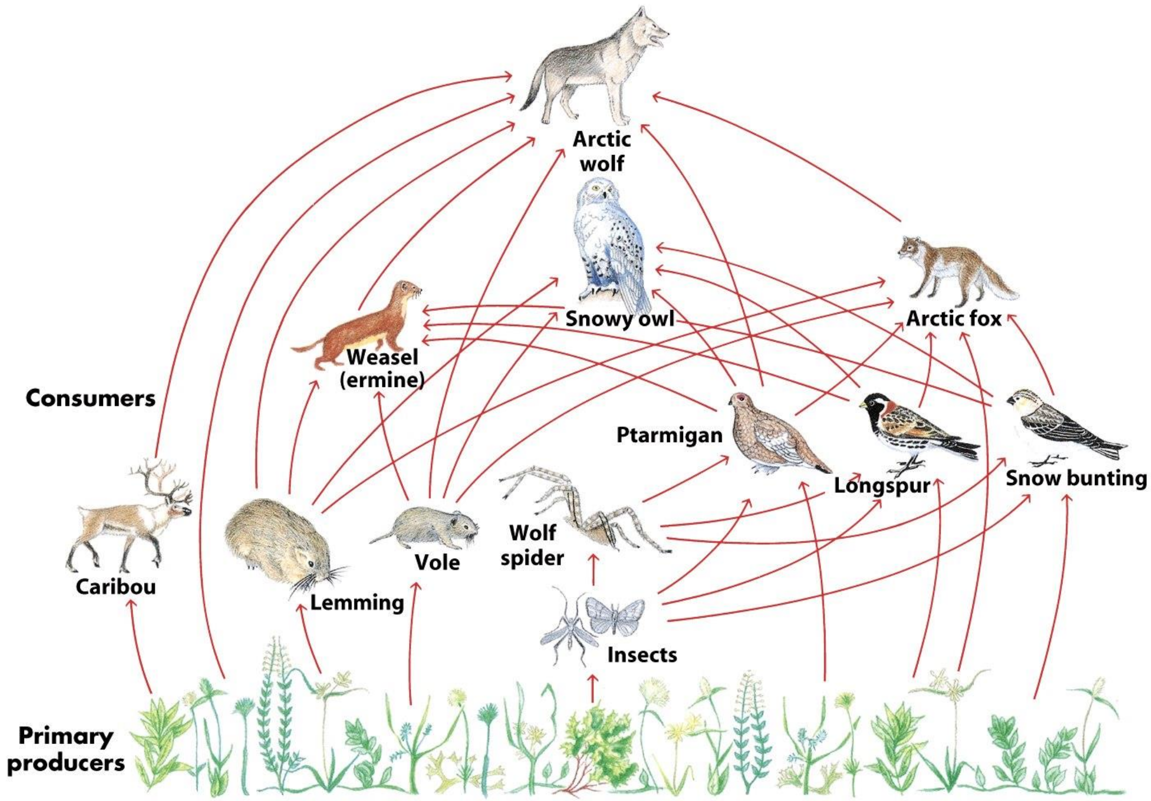


Figure 31-1
Biology of Plants, Seventh Edition

High level of quantitative content and reasoning skills are required

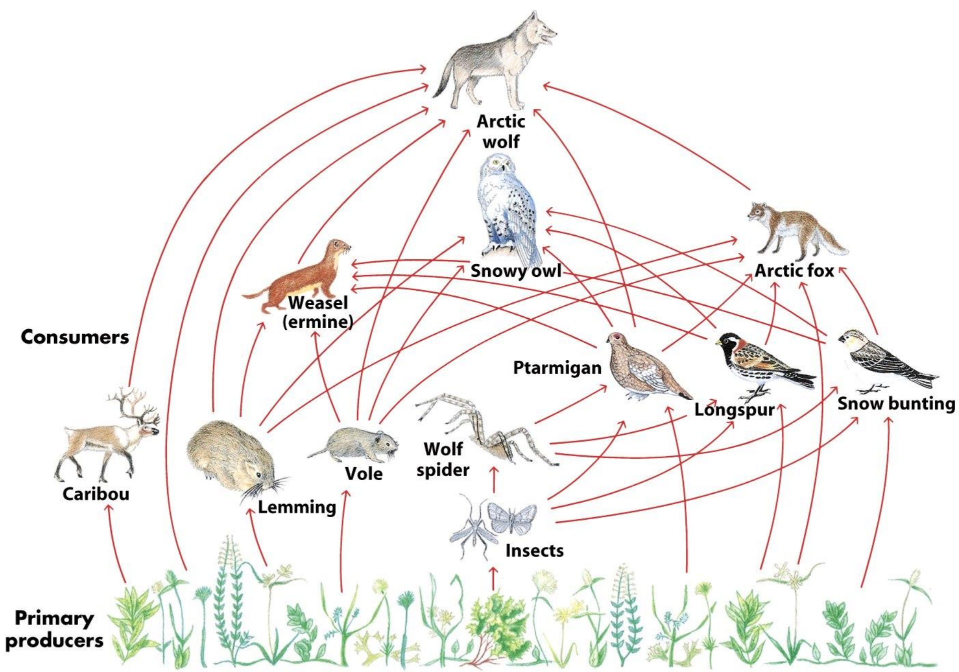


Figure 31-1
Biology of Plants, Seventh Edition

$$dX_i/dt = r_i X_i - \sum_j c_{ij} X_i X_j$$

$$dX_j/dt = - d_j X_j - \sum_k c_{jk} X_j X_k + e_j \sum_i c_{ij} X_i X_j$$

$$\begin{bmatrix} \alpha_{11} = -c_{11} X_1^* & \alpha_{12} = -c_{12} X_1^* \\ \alpha_{21} = a_2 p_2 c_{12} X_2^* & \alpha_{22} = 0 \end{bmatrix}$$

$$\lambda_{max} = \frac{\alpha_{11} + \sqrt{\alpha_{11}^{\ 2} + 4\alpha_{12}\alpha_{21}}}{2}$$

Planet Earth – Systems and Scale

Open Systems and Closed Systems

Open systems and closed systems are terms used to describe the level of interaction, communication, and exchange of resources between a system and its environment. These terms are commonly used in various fields such as physics, engineering, biology, and computing.

Open Systems and Closed Systems

- An open system is a system with inputs of energy or matter and outputs of energy or matter.
- A closed system is shut off from the surrounding environment so that it is self-contained. Closed systems are rare in nature.
- Earth system is an open system in terms of energy.
- Earth system is a closed system in terms of physical matter and resources.

Open Systems and Closed Systems

Open System: An open system is one that interacts with its environment, exchanging information, energy, and matter with the outside world. Open systems allow the flow of inputs and outputs between the system and its surroundings. These systems are characterized by their ability to adapt, evolve, and respond to changes in the environment. Open systems often have a higher degree of complexity due to the constant exchange of information and resources with their surroundings. Biological organisms, ecosystems, and many software applications are examples of open systems.

Key characteristics of open systems:

- Interaction with the environment.
- Exchange of energy, matter, and information.
- Adaptation and evolution based on external changes.
- Can achieve equilibrium with the environment.

Open Systems and Closed Systems

Closed System: A closed system is isolated from its environment and does not exchange matter with it, though energy or information might still be able to flow in or out. In a closed system, the total amount of matter remains constant, and no external matter is exchanged. While energy might still enter or leave the system, it's the matter that remains isolated. Closed systems are more common in theoretical or idealized contexts rather than in real-world situations. For example, the universe as a whole is often considered a closed system in terms of matter.

Key characteristics of closed systems:
- Limited or no interaction with the environment regarding matter exchange.
- Energy or information might still flow across the system boundary.
- Often used in theoretical contexts.
- Total matter remains constant within the system.

Earth as a System

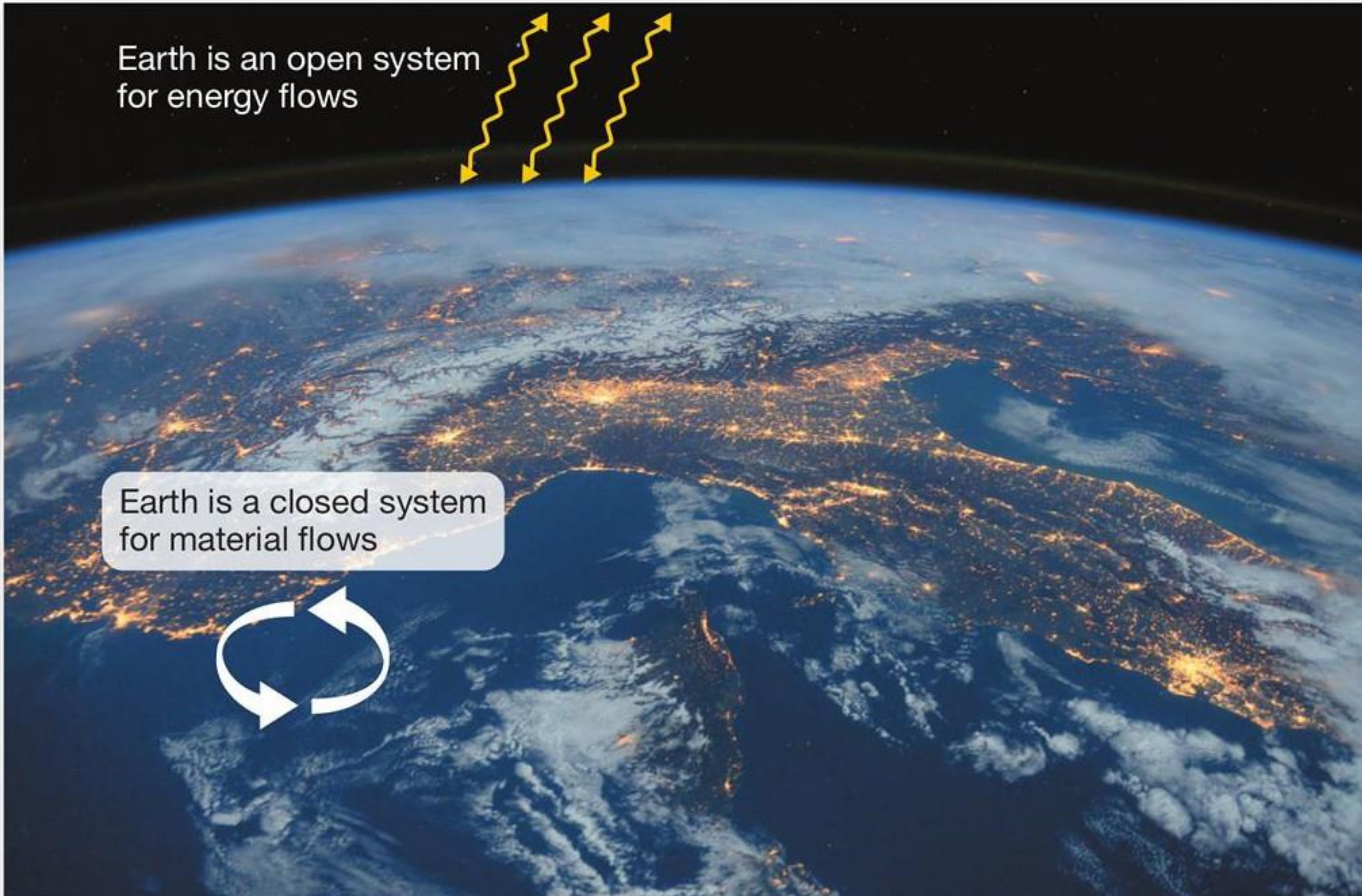


Figure1.6

Natural open system: a Forest

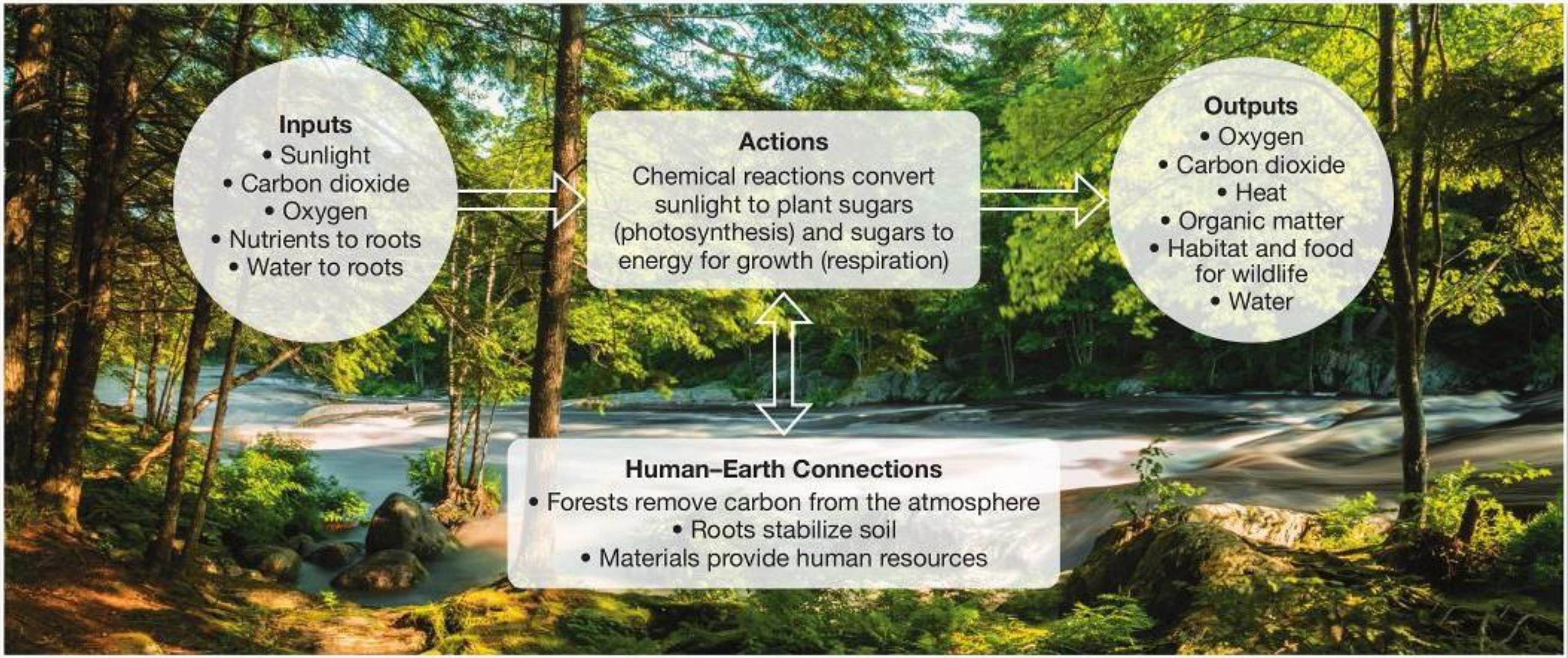


Figure 1.7

Conservation Laws of Mass and Energy

- Mass is neither destroyed nor created.
- Energy is the capacity to change the motion of, or to do work on, matter.
- Energy is neither destroyed nor created.
- Input − Output = Storage Change

Stoichiometery

The relationships between the quantities of reactants and products before, during, and following chemical reactions.

Primary Production
(Photosynthesis)
Inorganic → Organic
Immobilization

$$6CO_2 + 6H_20 \rightleftarrows C_6H_{12}0_6 + 60_2$$

Respiration
(Decomposition)
Organic → Inorganic
Mineralization

During photosynthesis, plants capture the energy in sunlight and convert the strong bonds between carbon and oxygen in CO_2 to the weak, reduced biochemical bonds in organic materials. As heterotrophic organisms, herbivores eat plants to extract this energy by capitalizing on the natural tendency for electrons to flow from reduced bonds back to oxidizing substances, such as O_2. Heterotrophs oxidize the carbon bonds in organic matter and convert the carbon back to CO_2. A variety of other metabolic pathways have evolved using transformations among other compounds (Chapters 2 and 7), but in every case metabolic energy is obtained from the flow of electrons between compounds in oxidized or reduced states. Metabolism is possible because living systems can sequester high concentrations of oxidized and reduced substances from their environment. Without membranes to compartmentalize living cells, thermodynamics would predict a uniform mix, and energy transformations, such as respiration, would be impossible.

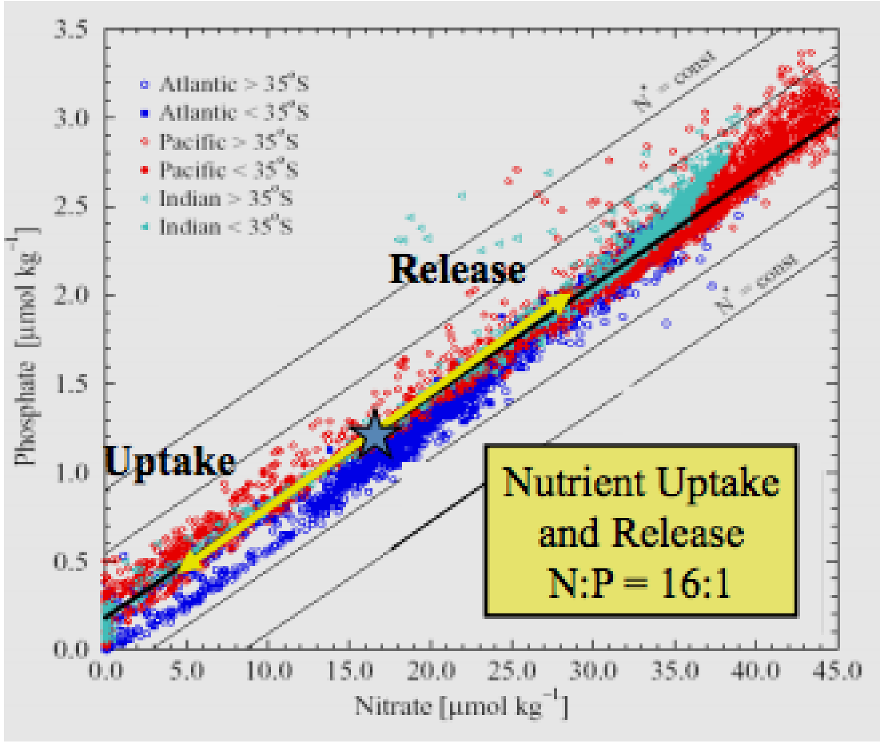
Oxidized $\longrightarrow$ Reduced

Reduced $\longrightarrow$ Oxidized

	H_2O/O_2	C	N	S
H_2O/O_2	X	Photosynthesis $CO_2 \longrightarrow C$ $H_2O \longrightarrow O_2$		
C	Respiration $C \longrightarrow CO_2$ $O_2 \longrightarrow H_2O$	X	Denitrification $C \longrightarrow CO_2$ $NO_3 \longrightarrow N_2$	Sulfate-Reduction $C \longrightarrow CO_2$ $SO_4 \longrightarrow H_2S$
N	Heterotrophic Nitrification $NH_4 \longrightarrow NO_3$ $O_2 \longrightarrow H_2O$	Chemoautotrophy (Nitrification) $NH_4 \longrightarrow NO_3$ $CO_2 \longrightarrow C$	Anammox $NH_4 + NO_2 \rightarrow N_2 + 2H_2O$	?
S	Sulfur Oxidation $S \longrightarrow SO_4$ $O_2 \longrightarrow H_2O$	Chemoautotrophy (Sulfur-based Photosynthesis) $S \longrightarrow SO_4$ $CO_2 \longrightarrow C$	Autotrophic Denitrification $S \longrightarrow SO_4$ $NO_3 \longrightarrow N_2/NH_4$	X

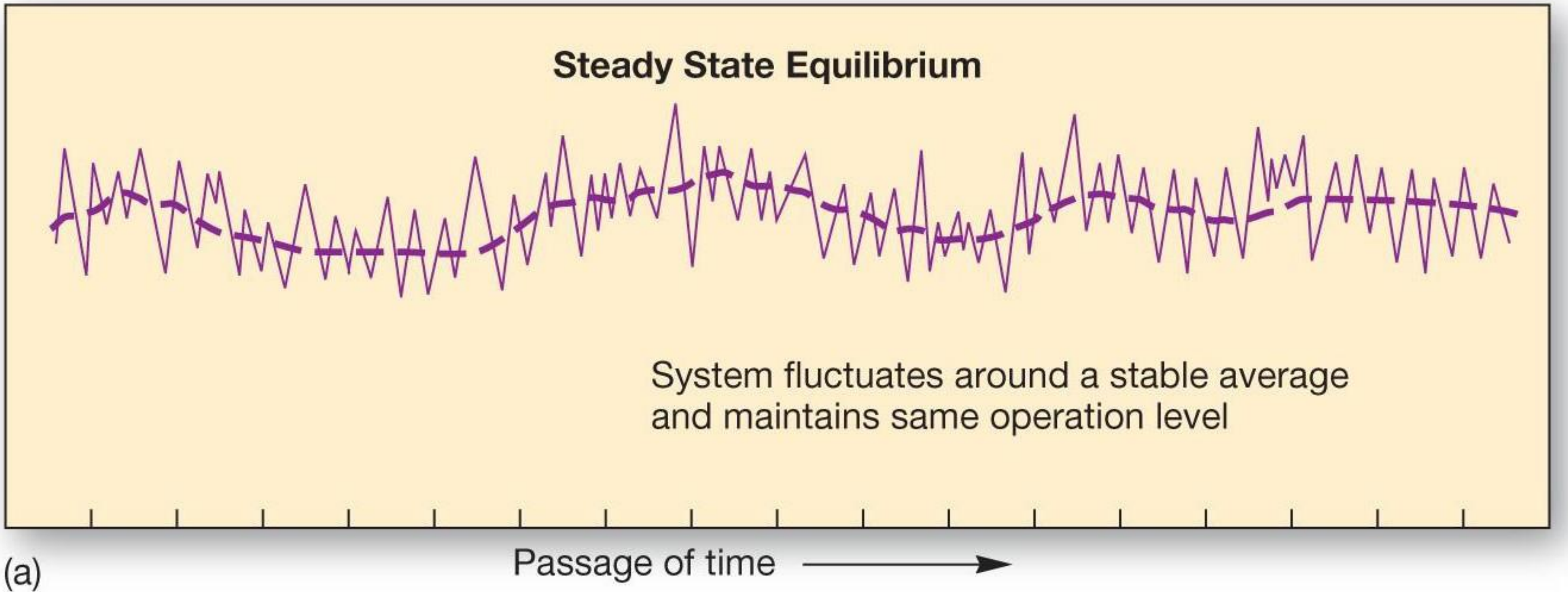
FIGURE 1.4 A matrix showing how cellular metabolisms couple oxidation and reduction reactions. The cells in the matrix are occupied by organisms or a consortium of organisms that reduce the element at the top of the column, while oxidizing an element at the beginning of the row. *Source: From Schlesinger et al. (2011).*

Redfield Ratio



Steady-State Equilibrium

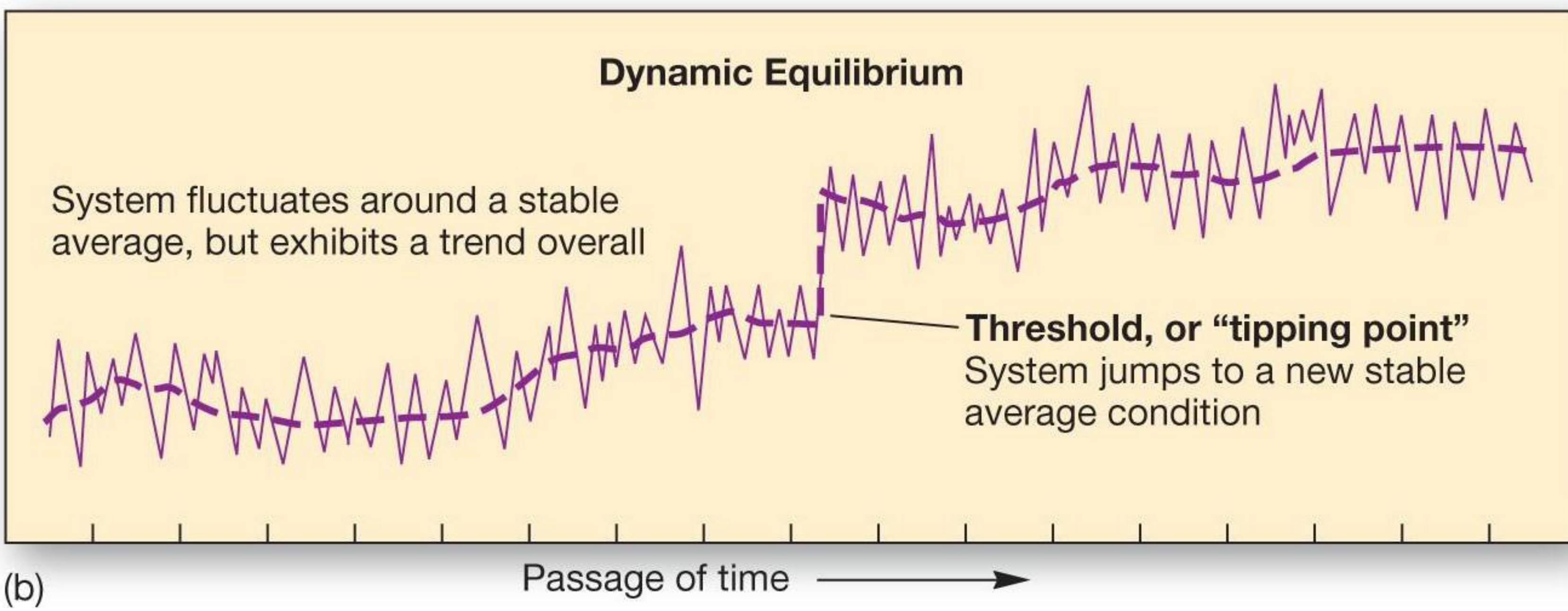
- Steady-state equilibrium: when the rates of inputs and outputs in the system are equal and the amounts of energy and matter in storage within the system are constant (or fluctuate around a stable average).



(a)

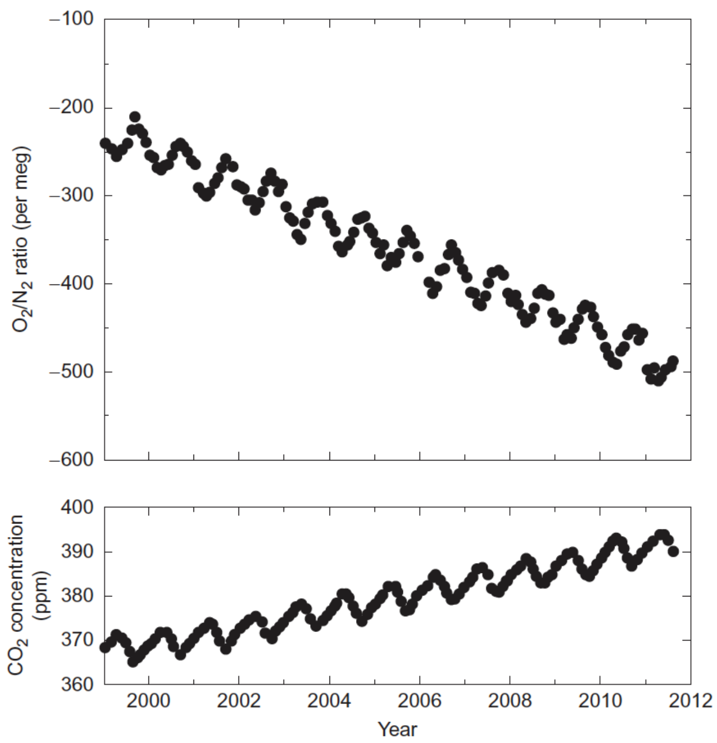
Dynamic Equilibrium

- Some systems are in a condition of dynamic equilibrium with an increasing or decreasing trend. A dynamic equilibrium system may change to a new operation level as it reaches a threshold called *tipping point*.



(b)

Processes and Timesteps



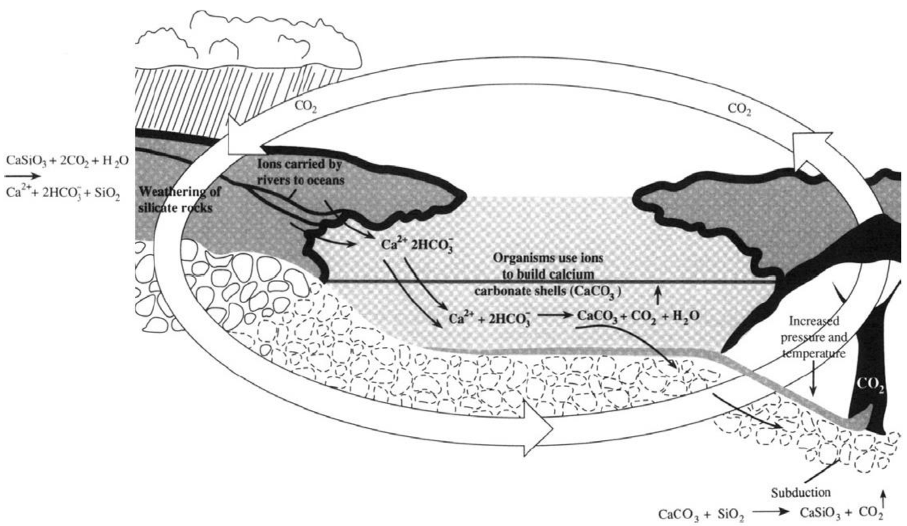


FIGURE 1.3 The interaction between the carbonate and the silicate cycles at the surface of Earth. Long-term control of atmospheric CO_2 is achieved by dissolution of CO_2 in surface waters and its participation in the weathering of rocks. This carbon is carried to the sea as bicarbonate (HCO_3^-), and it is eventually buried as part of carbonate sediments in the oceanic crust. CO_2 is released back to the atmosphere when these rocks undergo metamorphism at high temperature and pressures deep in Earth. *Source: Modified from Kasting et al. (1988).*

System Feedback

- Feedback loop: Outputs of a system influence the system’s operation
- Negative feedback
  - Feedback information discourages change in the system
  - a self regulation, stabilizes system
- Positive feedback
  - Feedback information encourages change in the system
  - destabilizes system

Arctic Sea Ice Positive Feedback Loop

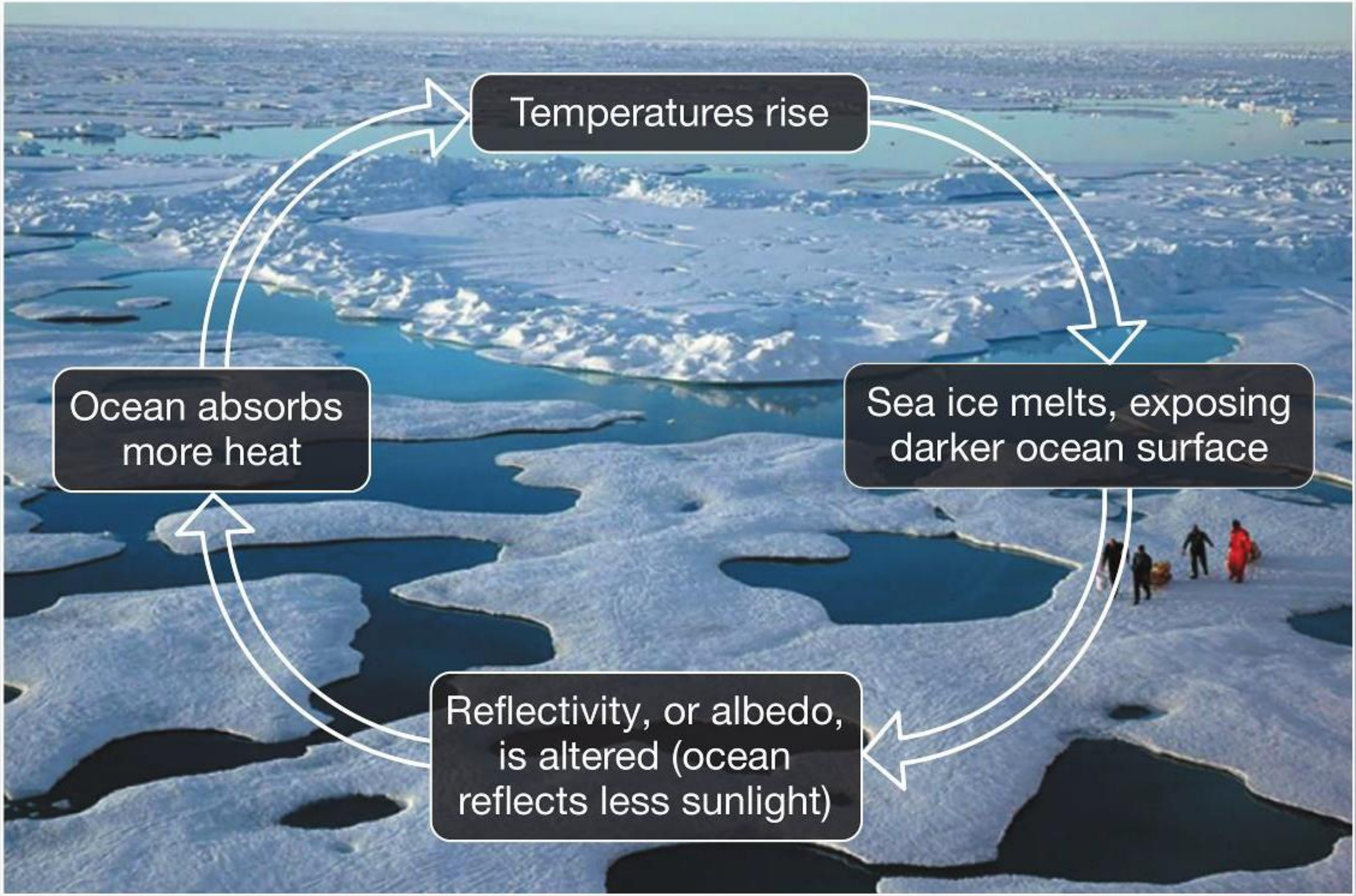


Figure 1.9

Models and Experimentation

Models of Systems:

Models are attempts by humans to simplify and display the functions of a system. They are only our best guess and they are never perfect. Examples include Black Box (not descriptive, only recognizes a system as such), Grey Box (intermediate level of description), and White Box, (An attempt at the highest level of description of components, structures, and processes of a system.).

" …In each of seven houses are seven cats; each cat kills seven mice; each mouse would have eaten seven ears of spelt (wheat); each ear of spelt would have produced seven hekat (half a peck) of grain. Query: How much grain is saved by the seven houses' cats?..."

Define the System in terms of the entities and components

Define the Boundaries

Identify the Controls and Feedbacks

What would Homeostasis look like

Boundaries

Initial conditions

Controls

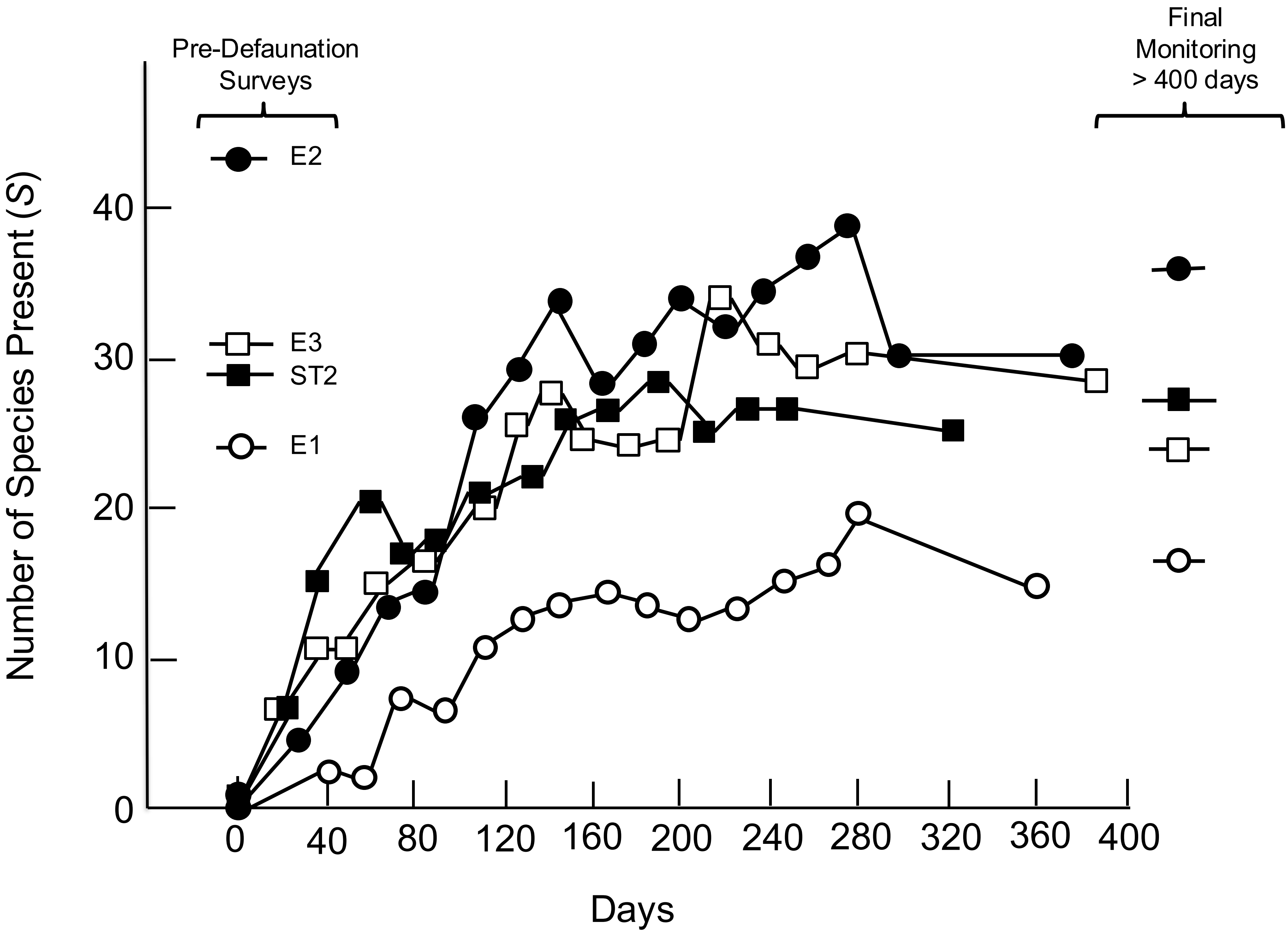
Feedbacks

Homoestatis

$$\frac{dX}{dt} = rX - sX^2 - cXY$$

$$\frac{dX}{dt} = rX - sX^2 - cXY$$

$$\frac{dY}{dt} = -dY - sY^2 + apcXY$$



Pre-Defaunation Surveys
Final Monitoring > 400 days
E2
E3
ST2
E1
Number of Species Present (S)
0
10
20
30
40
0
40
80
120
160
200
240
280
320
360
400
Days

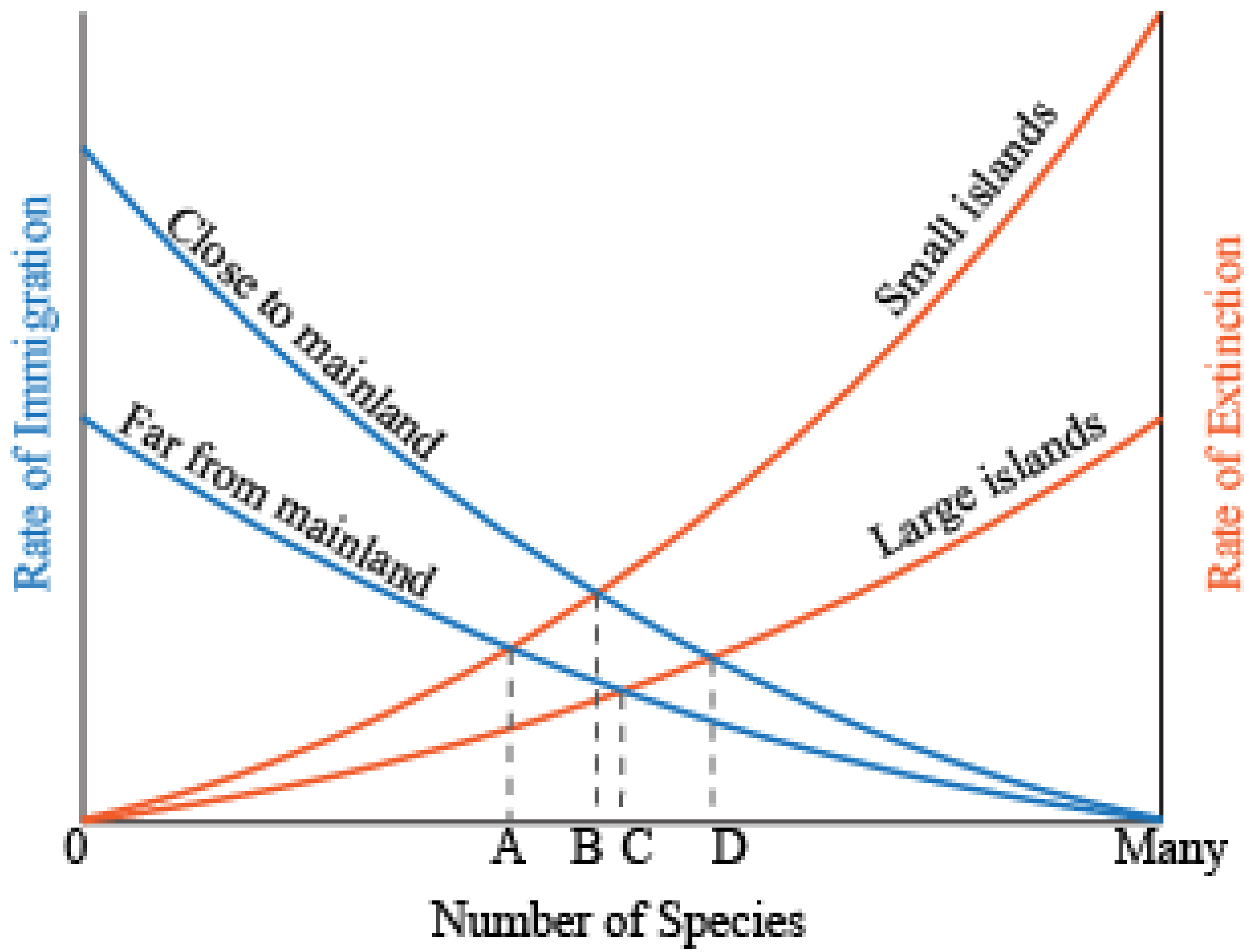
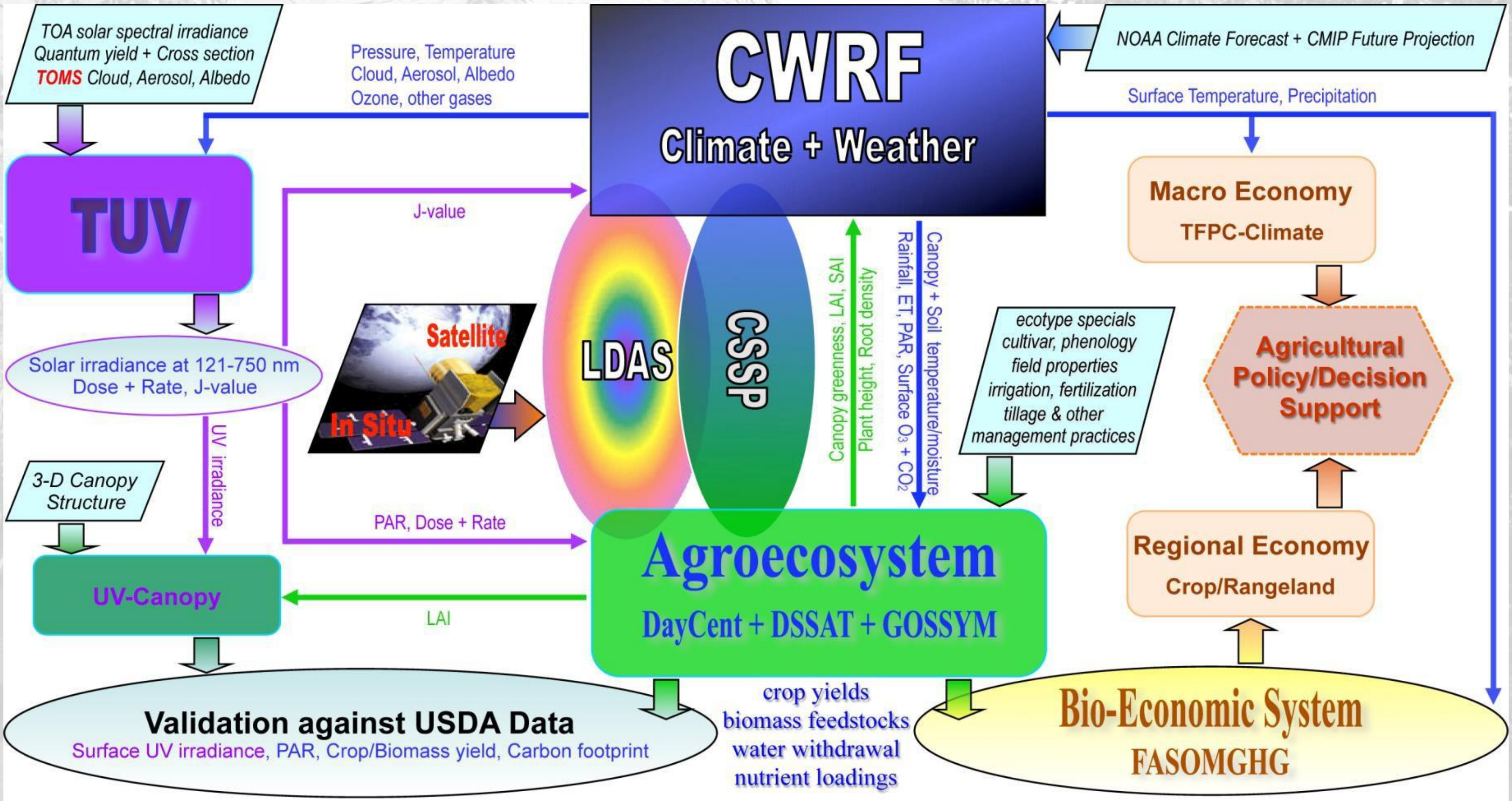

Rate of Immigration
Close to mainland
Far from mainland
Small islands
Large islands
Rate of Extinction
0
A
B
C
D
Many
Number of Species

FIGURE 1.5 An ecosystem-level experiment in which a lake was divided and one half (distant) fertilized with phosphorus, while the basin in the foreground acted as a control. The phosphorus-fertilized basin shows a bloom of nitrogen-fixing cyanobacteria. *Source: From Schindler (1974); www.sciencemag.org/content/184/4139/897.short. Used with permission.*

Modeling Work of UVB Program



CWRF: Climate-Weather Research and Forecasting model
CSSP: Conjunctive Surface-Subsurface Process model
LDAS: NASA/GSFC Land Data Assimilation System model
TUV: NCAR Tropospheric Ultraviolet-Visible radiation model

DayCent: Daily CENTURY biogeochemical model (grasses, crops, forests, savannas
DSSAT: Decision Support System for Agrotechnology Transfer model (crops)
GOSSYM: *Gossypium* cotton growth model **TFPC:** Total Factor Productivity Change
FASOMGHG: Forest and Agricultural Sector Optimization Model–GreenHouse Gases

LAI, SAI : Leaf, Stem Area Index
PAR: Photosynthetically-Active Radiation
J-value: Photodissociation coefficient
Dose + Rate: Biologically effective irradiance

Figure 1. The framework to predict Climate-Agroecosystem-UV interactions and Economic impacts for decision support.