1. (6 points)
a. Name the two major biological processes that are responsible for the coupling between the oxygen and carbon cycles. Write their reactions.

Photosynthesis: \( \text{CO}_2 + \text{H}_2\text{O} + \text{light} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \)
Respiration: \( \text{O}_2 + \text{CH}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy/ATP} \)

b. You measure the \( \text{CO}_2 \) concentration in the air over Alaska for one year and then plot your measured concentration minus the average annual concentration as a function of time. Explain the seasonal variation in \( \text{CO}_2 \) concentration illustrated in the figure below. Would you expect to see the same pattern if you measured \( \text{CO}_2 \) in the atmosphere over Chile? Why or why not?

![Graph of \( \Delta \text{CO}_2 \) concentration vs. month]

The increase in \( \text{CO}_2 \) from January-April is due to atmospheric mixing and respiration. As trees start to photosynthesize and the summer season begins, \( \text{CO}_2 \) drawdown occurs, reaching a maximum in July-August. The inflection point in September-October is due to reduced photosynthesis and increased respiration. Increasing \( \text{CO}_2 \) in November-December is again due to atmospheric mixing and respiration. In Chile, you would expect the seasonal cycle to be inverted with significantly dampened oscillations. This is a product of opposite seasons and less landmass in the Southern Hemisphere.

c. The \( \text{CO}_2 \) concentration in the atmosphere has increased drastically as a result of human activities over the past 100 years. In addition, the global \( \text{O}_2 \) concentration in the atmosphere has decreased, as shown in the graph below. Please explain the seasonal variation in each year and the overall 5-year trend in the figure.

![Graph of \( \Delta \text{O}_2 \) concentration vs. year]

The seasonality is a result of the production of \( \text{O}_2 \) by photosynthesis. The overall 5-year trend is caused by deforestation and the consumption of fossil fuels, which uses oxygen.
2. (7 points) You are a scientist studying elephant ecology in the Kibale Forest of Uganda. As part of your project you have collected the following data:

<table>
<thead>
<tr>
<th>Kibale Forest</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Primary Production</td>
<td>856.0 kcal m⁻² yr⁻¹</td>
</tr>
<tr>
<td>Total Biomass of Elephants</td>
<td>9.70 kcal m⁻²</td>
</tr>
<tr>
<td>Elephants</td>
<td></td>
</tr>
<tr>
<td>Food Consumed (I)</td>
<td>67.5 kcal m⁻² yr⁻¹</td>
</tr>
<tr>
<td>Fecal Material and Urine Lost (F)</td>
<td>30.2 kcal m⁻² yr⁻¹</td>
</tr>
<tr>
<td>Maintenance Metabolism (R)</td>
<td>36.8 kcal m⁻² yr⁻¹</td>
</tr>
<tr>
<td>Growth (P)</td>
<td>0.50 kcal m⁻² yr⁻¹</td>
</tr>
</tbody>
</table>

a. What is the exploitation efficiency of the elephants?

\[ \text{NPP} = \text{rate of plant biomass production} \]
\[ \text{C.E.} = \frac{\text{plants consumed}}{\text{total plants produced}} = \frac{67.5}{856} = 0.079 = 7.9\% \]

b. What is the assimilation efficiency of the elephants?

\[ \text{A.E.} = \frac{\text{A}_n}{I_n} \]
\[ \text{A}_n = \text{energy assimilated} = \text{energy ingested} - \text{energy lost in fecal material and urine} = 67.5 - 30.2 = 37.3 \]
\[ I_n = \text{food consumed} = 67.5 \]
\[ \text{A.E.} = \frac{37.3}{67.5} = 0.55 = 55\% \]

c. What is the production efficiency of the elephants?

\[ \text{Production of elephants} = \frac{P_n}{A_n} = \text{growth} = 0.5 \]
\[ \text{A}_n = \text{energy assimilated} = \text{energy ingested} - \text{energy lost in fecal material and urine} = 67.5 - 30.2 = 37.3 \]
\[ \text{P.E.} = \frac{0.5}{37.3} = 0.0134 = 1.34\% \]

d. Below is an energy flow diagram for one elephant, Babar. Sketch the energy flow diagram of Babar if he was cold-blooded.

3. (7 points) The population dynamics of a natural pond system are dictated solely by the food web pictured below. Water milfoil (*Myriophyllum*) is an invasive Eurasian genus of aquatic plants found in North American lakes and ponds. *Spirogyra* is a form of filamentous green algae that are native to North American freshwater ecosystems.

```
Trout                      Mosquito Larvae
                       \___________________________\
Snail                     Daphnia
                       \___________________________\
Milfoil                   Spirogyra
```

a. In order to help save the native *Spirogyra* population, you have a few measures available to you. You can either adjust the trout population (by adding more trout or by encouraging more fishing) or you can adjust the mosquito larvae population (by adding more larvae or by applying a biocide that only kills mosquito larvae). Which measure would be most effective at increasing the population of *Spirogyra*? Why? Clearly state all assumptions.

Increasing the population of mosquito larvae is the most direct method of increasing the population of *Spirogyra*. Increasing mosquito larvae will decrease the population of *Daphnia*, which feed exclusively on *Spirogyra*. There are a number of secondary effects that could be argued depending on the assumed time scale and response of populations.

b. A golf course is built upstream of the pond. The fertilizers from the runoff cause a 50% increase in the primary productivity of both milfoil and *Spirogyra*. By how much would you expect the productivity of snails and *Daphnia* to increase? Assume the ecological efficiency at each trophic level is 10%. Show calculations and explain your reasoning.

The productivity of snails and *Daphnia* will both increase by 50%. Assuming a trophic level transfer efficiency of 10%, we can project how the increase in productivity will cascade through the food web.

\[ P = \text{total primary productivity before golf course} \times 1.5 \times P = \text{total primary productivity after golf course} \]

Productivity of snails before golf course = 0.1\*P

Productivity of snails after golf course = 0.1\*1.5\*P

\[ \% \text{ increase} = 100\% \left( \frac{0.1\times1.5\times P - 0.1\times P}{0.1\times P} \right) = 50\% \]

4. (6 points) Al Gore has another idea for his new movie, *More Inconvenient Truths*. He wants you to assess the impacts of climate change on the hydrologic cycle.

a. How is the hydrologic cycle expected to change over the next century? Be sure to note sources in your answer.

Global warming is expected to accelerate the hydrologic cycle, effectively increasing global evapotranspiration and precipitation. Some snowfall will become rainfall. The melting of the snowpack and spring flood will occur earlier. Semi-arid regions are expected to experience more droughts. Sea level rise will result in saltwater intrusion of coastal aquifers.

b. Approximately 23% of the energy available at the Earth’s surface is used for evaporating water (either evaporation from free water surfaces or transpiration from plants). How much water, in km\(^3\) year\(^{-1}\), is evaporated? Assume the energy available at the surface of the Earth is 553 W m\(^{-2}\), the latent heat of vaporization is 2.5 x 10\(^{18}\) J kg\(^{-1}\), the density of water is 1.0 x 10\(^{12}\) kg km\(^{-3}\), the radius of Earth is 6.38 x 10\(^{6}\) m, and there are 31,536,000 seconds in a year.

\[ \text{Evap Energy} = 0.23 \times 553 \text{ W m}^{-2} = 127 \text{ W m}^{-2} \]

\[ 1 \text{ W m}^{-2} = 1 \text{ J s}^{-1} \text{ m}^{-2} \]

\[ \text{SA Earth} = 4 \times \pi \times (6.38 \times 10^{6})^2 = 5.1 \times 10^{14} \text{ m}^2 \]

\[ (127 \text{ J s}^{-1} \text{ m}^{-2} \times 31,536,000 \text{ s year}^{-1} \times 5.1 \times 10^{14} \text{ m}^2) / 2.5 \times 10^{18} \text{ J kg}^{-1} = 8.19 \times 10^{12} \text{ kg} \]

\[ 8.19 \times 10^{12} \text{ kg} / 1.0 \times 10^{12} \text{ kg km}^{-3} = 8.19 \times 10^{5} \text{ km}^3 \]

c. Compare your answer to the values given by Oki and Kanae. Give three potential reasons why your answer is different.

Our calculation

8.19 x 10\(^5\) km\(^3\)

Oki and Kanae

436,500 + 65,500 = 5.02 x 10\(^5\) km\(^3\)
Given our assumptions, we are fairly close. But, there are many possible reasons we are overestimating. We assume an unlimited supply of water and adequate transport of water vapor away from the evaporative surface. We’re using a ballpark estimate of the energy available at the Earth’s surface and an average density and latent heat of vaporization for water.

e. Al heard that climate change could lead to extensive droughts over the midwestern United States. The figure below contains the difference between renewable freshwater resources (RFWR) of the future climate (predicted) and current climate for the months of June, July, and August in mm day$^{-1}$. Should Al include droughts over the Midwest in his movie? Why or why not? What negative impacts of climate change might this figure miss? (Hint: Only the difference in 20-year averages of June, July, August RFWR is shown)

Al cannot put droughts over the Midwest as a detrimental effect of climate change in his new movie. The increase in precipitation is outpacing the increase in evaportranspiration, thus RFWR is increasing. A 20-year climatology does not adequately show extreme events (droughts and floods), which could have devastating effects on agriculture. Also, this is a model prediction with many potential inaccuracies.

5. (7 points) You’re a consultant for ENVIRON and are hired to investigate the declining freshwater fisheries of Lake Redfield. You quickly determine that reduced fish populations are a result of low dissolved O$_2$ levels caused by phytoplankton blooms. You measure the effluent of the wastewater treatment plant and find an N:P = 4:1. You then measure runoff from an adjacent farm and determine the N:P ratio is 28:1. Carbon is plentiful. You sample the lake every week for one summer and plot your results (black squares). Ignore the white circles for (a).

![Map of the United States with color gradient indicating difference in RFWR between future and current climate for June, July, and August.]

![Graph showing dissolved O$_2$ (mg/L) vs. PO$_4$ (mg/L) in Lake Redfield with black squares and a line of best fit.]

Image by MIT OpenCourseWare.
a. Assume the natural (before wastewater effluent and agriculture runoff) N:P ratio of Lake Redfield was 16:1. Who should be blamed for the phytoplankton blooms, the farmer or the wastewater treatment plant? Explain your reasoning.

Both are responsible for the heightened productivity because the Redfield ratio is exactly 16:1. The wastewater treatment plant contributes phosphorous and the farm contributes nitrogen.

b. The human population surrounding Lake Redfield doubles and the following year the phytoplankton blooms are even worse. You collect samples and plot your results (white circles). Is the lake nitrogen or phosphorous limited? Why?

The doubling of population increased the amount of wastewater effluent and thus the amount of phosphorous loading. Since the lake previously had an N:P ratio 16:1 and the ratio of N:P in wastewater effluent is 4:1, Lake Redfield is now nitrogen limited.

c. How would you expect the composition of the phytoplankton community to change between these two summers? (Hint: Think about different types phytoplankton)

The population of Cyanobacteria would increase because Lake Redfield is nitrogen limited. Cyanobacteria are capable of fixing nitrogen from the atmosphere, and would therefore have a competitive advantage over other phytoplankton.

d. Propose a solution to reduce the phytoplankton blooms in Lake Redfield.

Reduce the nutrient loading from the farm or wastewater treatment plant. The farm could use less fertilizer or treat runoff by nitrifying ammonia to nitrate and denitrifying nitrate to nitrogen gas. However, this is fairly impractical. Installing tertiary treatment to reduce the nitrogen and phosphorous loading from the wastewater treatment plant, which is a point source, would likely be much more cost effective.