Human Uses of the Biosphere and Impacts on Earth Systems

Ecosystems

IPOL 8512
Ecosystem Productivity

- **Productivity** or **production** = the rate of generation of biomass in an ecosystem. It can be expressed in units of mass per unit surface area per unit time, e.g. grams per square meter per year. The mass unit may relate to dry matter or to the mass of carbon generated.
Primary Productivity

• **Primary productivity** = the productivity of autotrophs, such as plants on land and algae in water.
  
  • It involves the synthesis of new organic material from inorganic molecules, such as H₂O and CO₂. It is dominated by the process of **photosynthesis**, which uses sunlight to synthesize organic molecules, such as sugars. A simplified reaction is

  \[
  \text{CO}_2 + \text{H}_2\text{O} + \text{light} \rightarrow \text{CH}_2\text{O} + \text{O}_2
  \]

  • **Chemosynthesis**, the biological conversion of one or more carbon molecules (usually carbon dioxide or methane) and nutrients into organic matter using the oxidation of inorganic molecules (e.g. hydrogen gas, hydrogen sulfide) or methane as a source of energy, represents a small fraction of primary production. A simplified sample reaction is

  \[
  \text{CO}_2 + \text{O}_2 + 4\ \text{H}_2\text{S} \rightarrow \text{CH}_2\text{O} + 4\ \text{S} + 3\ \text{H}_2\text{O}
  \]
Gross Primary Production, GPP

- Autotrophs
  \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{organic molecules}, \text{e.g. C}_6\text{H}_{12}\text{O}_6 \]
  Radiant energy \( \rightarrow \) chemical potential energy

- Energy stored in organic molecules supplies energy needs of both autotrophs and heterotrophs.

- Because there are lots of different organic molecules, the rate of formation of these molecules (mass of substances per time) can be described in terms of the mass of carbon in the substances formed per time, e.g. Gt(C)/y.

- The total rate of formation of these substances is called the gross primary production, GPP.
Net Primary Production, NPP

- The autotrophs convert some of the organic molecules that are part of the GPP back into CO$_2$ and H$_2$O in plant respiration to provide energy to run the autotroph (plant respiration).

- The portion that remains is available for autotroph growth and for the energy needs of heterotrophs. This is the net primary production, NPP, which is the difference between the rate at which the plants in an ecosystem produce useful chemical energy (GPP) and the rate at which they use some of that energy during autotroph respiration.

\[
\text{NPP} = \text{GPP} - \text{respiration [by plants]}
\]

- Both gross and net primary production can be expressed in units of mass/area/time, e.g. Gt(C)/m$^2$/y, or mass/time, Gt(C)/y.
GPP and NPP

\[ \text{CO}_2 + \text{H}_2\text{O} + \text{radiant energy} \rightarrow \text{higher energy organic molecules, e.g. } \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{GPP} \]

\[ \text{GPP} = \text{NPP} + \text{autotroph respiration (R)} \]

rate at which

higher energy organic molecules, e.g. \( \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy} \)

Rate of formation of more complex molecules that are available to provide energy for autotroph growth and heterotroph growth and respiration
Secondary Productivity

• **Secondary productivity** = the generation of biomass of heterotrophic (consumer) organisms in a system. It represents the quantity of new tissue created through the use of assimilated food.
  • Secondary productivity is sometimes defined to only include consumption of primary producers by herbivorous consumers (with tertiary production referring to carnivorous consumers), but is more commonly defined to include all biomass generation by heterotrophs.
  • Organisms responsible for secondary production include animals, fungi, and many bacteria.
Conversion of Solar Energy to Biomass

Simplified photosynthesis:

\[ \text{CO}_2 + \text{H}_2\text{O} + \text{energy} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

(Actual typical photosynthate: \( \text{C}_{1480}\text{H}_{2960}\text{O}_{1480}\text{N}_{160}\text{P}_{18}\text{S}_{10} \))

Simplified respiration or combustion:

\[ \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy} \]

“Fixing” 1 g of organic C requires about 40 kJ of energy.

“Burning” 1 g of organic C releases about 40 kJ of energy.
Global Estimates of GPP and NPP

- Global GPP \approx 200 \text{ Gt C/y} (\pm \text{large uncertainty})
- Global NPP \approx 100 \text{ Gt C/y} \pm 25 \text{ Gt C/y}
  - Estimate has gone up since Cow published: 75 \to 100
- Terrestrial NPP \approx 60 \text{ Gt C/y}
  - Varies widely by biome type; see Cow Appendix XII (old estimates)
- Ocean NPP \approx 50 \text{ Gt C/y} \pm 10 \text{ Gt C/y} (\text{hard to measure})

Problem:

- Calculate the joules of energy per year derived from the NPP of 100 \text{ Gt C/yr.}
Annual Energy from Global NPP

Calculate the joules of energy per year derived from the NPP of 100 Gt C/yr.

\[
\frac{? \text{ J}}{1 \text{ yr}} = \frac{100 \text{ Gt C}}{1 \text{ yr}} \left( \frac{10^9 \text{ t}}{1 \text{ Gt}} \right) \left( \frac{10^6 \text{ g}}{1 \text{ t}} \right) \left( \frac{40 \text{ kJ}}{1 \text{ g C}} \right) \left( \frac{10^3 \text{ J}}{1 \text{ kJ}} \right) \approx 4.0 \times 10^{21} \text{ J/yr}
\]
NPP Percentage of Total Solar Radiation

• Calculate the power in TW derived from 100 Gt C/yr. What percentage of the total solar radiation (100,000 TW) is this?
NPP Percentage of Total Solar Radiation

- Calculate the power in TW derived from 100 Gt C/yr. What percentage of the total solar radiation (100,000 TW) is this?

\[
? \text{TW} = \frac{100 \text{ Gt C}}{1 \text{ yr}} \left( \frac{10^9 \text{ t}}{1 \text{ Gt}} \right) \left( \frac{10^6 \text{ g}}{1 \text{ t}} \right) \left( \frac{40 \text{ kJ}}{1 \text{ g C}} \right) \left( \frac{10^3 \text{ J}}{1 \text{ kJ}} \right) \left( \frac{1 \text{ W s}}{1 \text{ J}} \right) \left( \frac{1 \text{ TW}}{10^{12} \text{ W}} \right) \left( \frac{1 \text{ yr}}{365 \text{ day}} \right) \left( \frac{1 \text{ day}}{24 \text{ hr}} \right) \left( \frac{1 \text{ hr}}{60 \text{ min}} \right) \left( \frac{1 \text{ min}}{60 \text{ s}} \right) \approx 130 \text{ TW}
\]

\[
? \frac{\text{TW NPP}}{\text{TW solar}} \times 100 = \frac{130 \text{ TW NPP}}{100,000 \text{ TW solar}} \times 100 = 0.13\%
\]

- In a sense, this is the efficiency with which the planet uses solar energy.
Conversion Between Mass Carbon and Mass Biota

• We can approximate the chemical composition of living things as CH$_2$O and water. A better approximation is H$_{2960}$O$_{1480}$C$_{1480}$N$_{160}$P$_{18}$S$_{10}$. It is useful to be able to convert between mass of CH$_2$O and mass of carbon or between mass of H$_{2960}$O$_{1480}$C$_{1480}$N$_{160}$P$_{18}$S$_{10}$ and mass of carbon. Calculate the conversion factors that will make these conversions.
Carbon to Biomass Ratio

If \( CH_2O \approx \text{biomass} \)

\[
\frac{? \text{ g C}}{\text{g CH}_2\text{O}} = \frac{1 \text{ mol C}}{1 \text{ mol CH}_2\text{O}} \left( \frac{12.011 \text{ g C}}{1 \text{ mol C}} \right) \left( \frac{1 \text{ mol CH}_2\text{O}}{30.0263 \text{ g CH}_2\text{O}} \right)
\]

\[
= \frac{0.40002 \text{ g C}}{1 \text{ g CH}_2\text{O}} \approx \frac{0.40002 \text{ g C}}{1 \text{ g biomass}}
\]

If \( H_{2960}O_{1480}C_{1480}N_{160}P_{18}S_{10} \approx \text{biomass} \)

\[
\frac{? \text{ g C}}{\text{g biomass}} = \frac{1480 \text{ mol C}}{1 \text{ mol biomass}} \left( \frac{12.011 \text{ g C}}{1 \text{ mol C}} \right) \left( \frac{1 \text{ mol biomass}}{47558.155 \text{ g biomass}} \right)
\]

\[
= \frac{0.37378 \text{ g C}}{1 \text{ g biomass}}
\]
Mass of Living Things

• It has been estimated that there are about 700 Gt C in living biota. If we approximate the chemical composition of living things as CH₂O and water, what is the approximate *dry* mass in metric tons of Earth’s living things? If we use $\text{H}_{2960}\text{O}_{1480}\text{C}_{1480}\text{N}_{160}\text{P}_{18}\text{S}_{10}$ as the formula for dry biomass, what is the approximate *dry* mass in metric tons of Earth’s living things?
Mass of Living Things

\[ \text{? Gt CH}_2\text{O} = 700 \text{ Gt C} \left( \frac{1 \text{ Gt CH}_2\text{O}}{0.40002 \text{ Gt C}} \right) \approx 1700 \text{ Gt biomass} \]

\[ \text{? Gt H}_{2960}\text{O}_{1480}\text{C}_{1480}\text{N}_{160}\text{P}_{18}\text{S}_{10} = 700 \text{ Gt C} \left( \frac{1 \text{ Gt H}_{2960}\text{O}_{1480}\text{C}_{1480}\text{N}_{160}\text{P}_{18}\text{S}_{10}}{0.37378 \text{ Gt C}} \right) \]

\[ \approx 1900 \text{ Gt biomass} \]

- Most Earths biomass is in terrestrial plants – trees, shrubs, and grasses. The woody parts of terrestrial plants are about 50% free water, the leafy parts about 75%. As a rough estimate of the average, assume living things altogether are 2/3 water and 1/3 dry organic matter (DOM).

- What is the approximate wet mass of living matter?
Wet Mass of Living Things

? Gt biota = 1900 Gt DOM \left( \frac{3 \text{ Gt biota}}{1 \text{ Gt DOM}} \right) \approx 6000 \text{ Gt biota}

- Biota have mass 1,000 times less than atmosphere, but contain a similar amount of carbon.
The human population is about 6.8 billion people. The average human energy consumption is about 2500 Calories per day. Using the NPP given on page 16 of COW of $7.5 \times 10^{16}$ g(C)/yr, calculate fraction of the total annual plant growth on Earth that is eaten by humans?
The human population is about 6.8 billion people. The average human energy consumption is about 2500 Calories per day. Using the NPP given on page 16 of COW of $7.5 \times 10^{16}$ g(C)/yr, calculate fraction of the total annual plant growth on Earth that is eaten by humans?

\[
\frac{? \text{ J}}{\text{yr}} = 6.8 \times 10^9 \text{ pers.} \left( \frac{2500 \text{ Cal}}{1 \text{ day} \cdot \text{pers.}} \right) \left( \frac{4184 \text{ J}}{1 \text{ Cal}} \right) \left( \frac{365 \text{ day}}{1 \text{ yr}} \right)
\]

\[= 2.6 \times 10^{19} \text{ J/yr}\]

\[
\frac{? \text{ g C}}{\text{g C}_6\text{H}_{12}\text{O}_6} = \frac{12.011 \text{ g C}}{1 \text{ mol C}} \left( \frac{6 \text{ mol C}}{1 \text{ mol C}_6\text{H}_{12}\text{O}_6} \right) \left( \frac{1 \text{ mol C}_6\text{H}_{12}\text{O}_6}{180.158 \text{ g C}_6\text{H}_{12}\text{O}_6} \right)
\]

\[= \frac{0.40002 \text{ g C}}{1 \text{ g C}_6\text{H}_{12}\text{O}_6} \approx \frac{0.40002 \text{ g C}}{1 \text{ g biomass}}\]

\[
\frac{? \text{ kJ total}}{\text{yr}} = \frac{7.5 \times 10^{16} \text{ g C}}{1 \text{ yr}} \left( \frac{1 \text{ g biomass}}{0.40002 \text{ g C}} \right) \left( \frac{1.6 \times 10^4 \text{ J}}{1 \text{ g biomass}} \right)
\]

\[= 3.0 \times 10^{21} \text{ kJ/yr}\]

\[
\frac{? \text{ J/yr pers}}{\text{J/yr total}} = \frac{2.6 \times 10^{19} \text{ J/yr}}{3.0 \times 10^{21} \text{ J/yr}} = 0.0086 \text{ or } 0.86\%\]
Land Cover

- Earth’s land area =
  30% land • 500×10^6 km^2 total = 150×10^6 km^2

- Quick rule of thumb:
  (see *Cow* Appendix XII for more precise figures)
  
  Forest = 50 × 10^6 km^2
  Other Productive Land = 50 × 10^6 km^2
  “Wasteland” = 50 × 10^6 km^2
Earth’s Biomes

- NPP differs greatly between different biomes.
- **Biome** = A major regional or global biotic community, such as a grassland or desert, characterized chiefly by the dominant forms of plant life and the prevailing climate.
- Biomes can be classified in different ways, but there are about a dozen major types.
Earth’s Biomes
Biome distribution is governed by temperature and precipitation.

after Whittaker, 1975
## Carbon Stocks and NPP of Terrestrial Biomes

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Area ($10^{12}$ m$^2$)</th>
<th>NPP (Pg C/y)</th>
<th>Plant C (Pg)</th>
<th>Soil C (Pg)</th>
<th>NPP/area (kgC/m$^2$·y)</th>
<th>NPP/Plant C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest, tropical</td>
<td>14.8</td>
<td>13.7</td>
<td>244</td>
<td>123</td>
<td>0.93</td>
<td>6%</td>
</tr>
<tr>
<td>Forest, temperate</td>
<td>7.5</td>
<td>5</td>
<td>92</td>
<td>90</td>
<td>0.67</td>
<td>5%</td>
</tr>
<tr>
<td>Forest, Boreal</td>
<td>9</td>
<td>3.2</td>
<td>22</td>
<td>135</td>
<td>0.36</td>
<td>15%</td>
</tr>
<tr>
<td>Woodland, temperate</td>
<td>2</td>
<td>1.4</td>
<td>16</td>
<td>24</td>
<td>0.70</td>
<td>9%</td>
</tr>
<tr>
<td>Chaparral</td>
<td>2.5</td>
<td>0.9</td>
<td>8</td>
<td>30</td>
<td>0.36</td>
<td>11%</td>
</tr>
<tr>
<td>Savanna, tropical</td>
<td>22.5</td>
<td>17.7</td>
<td>6</td>
<td>264</td>
<td>0.79</td>
<td>295%</td>
</tr>
<tr>
<td>Grassland, temperate</td>
<td>12.5</td>
<td>4.4</td>
<td>9</td>
<td>295</td>
<td>0.35</td>
<td>49%</td>
</tr>
<tr>
<td>Tundra, arctic/alpine</td>
<td>9.5</td>
<td>1</td>
<td>6</td>
<td>121</td>
<td>0.01</td>
<td>2%</td>
</tr>
<tr>
<td>Desert and scrub</td>
<td>21</td>
<td>1.4</td>
<td>7</td>
<td>168</td>
<td>0.07</td>
<td>20%</td>
</tr>
<tr>
<td>Desert, extreme</td>
<td>9</td>
<td>0.1</td>
<td>0</td>
<td>23</td>
<td>0.01</td>
<td>n/a</td>
</tr>
<tr>
<td>Perpetual ice</td>
<td>15.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Lake and stream</td>
<td>2</td>
<td>0.4</td>
<td>0</td>
<td>-</td>
<td>0.20</td>
<td>n/a</td>
</tr>
<tr>
<td>Wetland</td>
<td>2.8</td>
<td>3.3</td>
<td>12</td>
<td>202</td>
<td>1.18</td>
<td>28%</td>
</tr>
<tr>
<td>Peatland</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
<td>455</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Cultivated</td>
<td>14.8</td>
<td>6.3</td>
<td>3</td>
<td>117</td>
<td>0.43</td>
<td>210%</td>
</tr>
<tr>
<td>Human area</td>
<td>2</td>
<td>0.2</td>
<td>1</td>
<td>10</td>
<td>0.10</td>
<td>20%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>150.8</strong></td>
<td><strong>59</strong></td>
<td><strong>486</strong></td>
<td><strong>2057</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The amount of standing biomass (C stock) is *not* necessarily correlated the flow of new biomass (NPP) (contrast e.g. tropical savannah and arctic tundra).

- Financial analogy:
  - Biomass stock = total amount in your bank account
  - NPP = flow = how much you deposit each month

Diagram:
- NPP
- Biomass stock
  - Decomposition
  - Primary consumption
  - Human use
How do humans use NPP?

- Food
- Fodder
- Fuel
- Fiber
- Building materials
- Other *(medicine, dye, household goods...)*

Some economies depend on NPP more directly than others. For example, in Malawi:

- 90% of the population are subsistence farmers
- 90% depend on wood as primary energy source
- 86% of export earnings are from tobacco and other cash crops
Human Impacts on Oceans

- We don’t consume ocean water as we do freshwater, but still have significant effects:
  - Fishing
  - Pollution
  - Global climate change:
    - Increased sea surface temperature
    - Increased storm intensity
    - Acidification (due to increased CO₂)
    - Sea level rise
- Fisheries are an urgent concern. 52% of all stocks are fully exploited and 28% are overexploited. Extrapolating current trends, all ocean fish will be gone by 2048!

Human Impact on Marine Ecosystems

• The authors of the paper, *A Global Map of Human Impact on Marine Ecosystems* by B. S. Halpern, et al in Science 2008;319:948-952 conclude that, “Our analysis indicates that no area [of the world’s oceans] is unaffected by human influence and that a large fraction (41%) is strongly affected by multiple drivers.”

• Land-based activities affect the runoff of pollutants and nutrients into coastal waters and remove, alter, or destroy natural habitat.

• Ocean-based activities extract resources, add pollution, and change species composition.
Human Impact on Marine Ecosystems

- Over a third (41%) of the world's oceans have medium high to very high [impact], with a small fraction (0.5%) but relatively large area (~2.2 million km²) experiencing very high impact.
- Most of the highest predicted cumulative impact is in areas of continental shelf and slope, which are subject to both land- and ocean-based anthropogenic drivers.
- Large areas of high predicted impact occur in the North and Norwegian seas, South and East China seas, Eastern Caribbean, North American eastern seaboard, Mediterranean, Persian Gulf, Bering Sea, and the waters around Sri Lanka.

B S Halpern et al. Science 2008;319:948-952
Histogram of cumulative impact scores depicting the fraction of global area that falls within each impact category.
The distribution of cumulative impact scores for each ecosystem in our analyses (means in parentheses)

B S Halpern et al. Science 2008;319:948-952
Total area affected (square kilometers, grey bars) and summed threat scores (rescaled units, black bars) for each anthropogenic driver (A) globally and (B) for all coastal regions <200 m in depth.
Ocean Impacts of Anthropogenic Climate Change

- Decreased ocean productivity,
- Altered food web dynamics,
- Reduced abundance of habitat-forming species,
- Shifting species distributions,
- A greater incidence of disease.

O Hoegh-Guldberg, J F Bruno
Science 2010;328:1523-1528
Less Understanding of Effect of Climate Change on Ocean Ecosystems

- Due to the size and complexity of the ocean,
- And relative difficulty of taking measurements in marine environments.

O Hoegh-Guldberg, J F Bruno
Science 2010;328:1523-1528
According to the authors of *The Impact of Climate Change on the World’s Marine Ecosystems* (O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528), “the heat content of the upper 700 m of the global ocean has increased by $14 \times 10^{22}$ J since 1975, with the average temperature of the upper layers of the ocean having increased by 0.6°C over the past 100 years.

Global ocean surface temperatures in January 2010 were the second warmest on record for the month of January, and the period June to August 2009 reached 0.58°C above the average global temperature recorded for the 20th century, 16.4°C.”
Effect of CO$_2$ Absorption in Ocean

- Oceans have absorbed approximately one-third of the carbon dioxide produced by human activities.
- The absorption of anthropogenic CO$_2$ has acidified the surface layers of the ocean, with a steady decrease of 0.02 pH units per decade over the past 30 years and an overall decrease since the pre-industrial period of 0.1 pH units.
- Although these increases appear small in terms of pH, they are associated with a substantial decline in the concentration of carbonate ions.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Recent changes in ocean temperature, acidity, and carbonate ion concentration.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Other Effects of Climate Change on Oceans

- **Increased ocean volume and sea level from**
  - Thermal expansion of the oceans
  - Increased meltwater and discharged ice from terrestrial glaciers and ice sheets

- **Warmer oceans also drive more intense storm systems and other changes to the hydrological cycle.**

- **The warming of the upper layers of the ocean also drives greater stratification of the water column, reducing mixing in some parts of the ocean and consequently affecting nutrient availability and primary production. These changes have increased the size of the nutrient-poor “ocean deserts” of the Pacific and Atlantic by 6.6 million km², or 15%, over the period 1998 to 2006.**

- **General circulation models also predict that oxygen concentrations in the upper layers of the ocean are likely to decrease as a consequence of increasing stratification.**

  O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Other Effects of Climate Change on Oceans

- Changes in the behavior of ocean currents have the potential to strongly influence the distribution and abundance of marine ecosystems.
- Some of the most striking impacts of global climate change have appeared in polar oceans, where Temperatures and acidities of the polar oceans are changing at more than twice the global average.
- Arctic sea ice is steadily decreasing, its area being 16.5 million km$^2$ in March 1979 but reduced to 15.25 million km$^2$ by March 2009.
- Summer sea ice (measured in September each year) is projected to disappear completely by 2037.
- Satellite altimeter data reveal that the average global sea level is changing at a rate of 3.3 ± 0.4 mm/year (over the period 1993–2006).

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
(A and B) Average rate of global sea level rise (1993–2010) from TOPEX/Poseidon and Jason satellite altimetry data, shown as a map (A) and as a global mean sea level (B).
Temperature Effect on Organisms

- Increases in temperature increase metabolic rates, which ultimately determine life history traits, population growth, and ecosystem processes.

- Organisms tend to adapt to local environmental temperatures, with optimal physiological responses matching temperatures that are close to the environmental average.

- Organisms are able to acclimatize to a range of temperatures around these optimal values. Beyond this range, however, acclimatization fails, mortality risk increases, fitness is reduced, and populations decline or are driven to local extinction.
NPP of Oceans

- The annual primary production of the world’s oceans has decreased by at least 6% since the early 1980s, with nearly 70% of this decline occurring at higher latitudes and with large relative decreases occurring within Pacific and Indian ocean gyres.

- These findings have implications for the ability of [ocean organisms] to capture and store carbon dioxide, with the potential for these critical ocean processes to decline as temperature increases. Warming has also been found to decrease the size of individual phytoplankton, further altering the functioning and biogeochemistry of shallow pelagic ecosystems and, in particular, reducing their potential for carbon sequestration.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Reduced Habitat Complexity

- Although mangrove deforestation (1 to 2% per year) represents a greater near-term threat, risks from sea level are increasing, with expected losses of 10 to 20% of mangroves by 2100.

- Sea ice, like coral reefs and kelp forests, plays a critical role in structuring the biodiversity of polar oceans. The spring melt has a major role in determining the timing of phytoplankton blooms and consequently influences polar marine food web dynamics.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Other Effects

- A rising number of species are expanding their ranges, often with large-scale impacts on ecosystems at the destination.
  - For example, the southeastern Australian sea urchin Centrostephanus rodgersii (Diadematidae) has recently expanded its range into Tasmanian waters, where it has transformed macroalgal communities into taxonomically impoverished “urchin barrens”.

- Climate change has been implicated in recent variation in the prevalence and severity of disease outbreaks within marine ecosystems.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Coral Reefs and Carbonate Balance

- Increasing ocean temperatures and acidities associated with atmospheric CO$_2$ concentrations of 450 parts per million (ppm) represent a serious threat to ecosystems, such as coral reefs.

- Temperatures that exceed 2°C above pre-industrial temperatures are very likely to drive an unsustainable frequency of mass coral bleaching and mortality.

- Ocean acidification associated with atmospheric CO$_2$ above 450 ppm will push coral reefs into a negative carbonate balance.

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Marine ecosystems are already responding to the rapid pace of change in the physical and chemical conditions that surround them.

**Box 1.** Marine ecosystems are already responding to the rapid pace of change in the physical and chemical conditions that surround them (see table S2 for summary of recent literature). One of the most important impacts has been on the organisms and physical processes that create habitat for millions of other species. (A) Heron Island, southern Great Barrier Reef. Coral Reef ecosystems are declining because of anomalously warm sea temperatures, which are driving an increased frequency of coral bleaching and mortality. These impacts are combining with local impacts, as well as the slowing of reef accretion due to the impact of ocean acidification. Complex coral-dominated reef ecosystems like this one are likely to be rare by 2050. (B) Kelp forest (*Macrocystis pyrifera*, with California bat ray, *Myllobatis californica*) near San Clemente Island, California, USA. Warming ocean temperatures are driving a major contraction in the distribution of kelp forests worldwide. (C) Daintree River, northeastern Australia. Mangroves are critically important coastal habitat for numerous coastal species. The loss of 10 to 20% of mangroves is projected if sea levels rise by 1 m above today. (D) The loss of summer sea ice by 2040 in the Arctic will have a strong impact on a range of dependent organisms, both above and below the ice. [Credits: (A) and (C) O. Hoegh-Guldberg; (B) Philip Colla, www.Oceanlight.com; (D) Daniel J. Cox, www.NaturalExposures.com]

O Hoegh-Guldberg, J F Bruno Science 2010;328:1523-1528
Total human appropriation of NPP

Total appropriation of NPP by humans = 20-25 Gt C

= 30-40% of terrestrial NPP

- Direct consumption = 2.4 Gt C/y out of 60 Gt C/y
  = 4% of NPP

- Cooptation + consumption = 18.5 Gt C out of 60 Gt C/y
  = 30% of NPP

- Lost opportunities + cooptation + consumption
  = 27.5 Gt C out of 68 Gt C = 40% of NPP

- Use of ocean NPP ≈ 8%

Human Appropriation of Net Primary Production (grams of carbon per year)
Land, Soils, and Ecosystems
Human influence is ubiquitous.

- There is virtually no part of the land surface that remains unaffected by human activities:
  - Polar regions receive atmospheric pollutants.
  - Hawaiian rainforests are infested with invasive plants.
  - Remote islands are affected by sea level rise.
- However, in this section we will focus on direct land use effects.
Human Land Uses

- Potentially land suitable for crops
  \[= 30 \times 10^6 \text{ km}^2 = 20\% \text{ of Earth’s land surface.} \]
  Virtually all is used.
- Cropland \[= 15 \times 10^6 \text{ km}^2 = 10\% \text{ of land surface}\]
  - Irrigated cropland \[= 3 \times 10^6 \text{ km}^2 = 2\% \]
- Grazing \[= 10 \times 10^6 \text{ km}^2 = 7\% \]
- Managed forests \[= 5 \times 10^6 \text{ km}^2 = 3\% \]
- Urbanization \[= 2 \times 10^6 \text{ km}^2 = 1\% \]
- Reservoirs, dams, canals
  \[= 0.3 \times 10^6 \text{ km}^2 = 0.2\% \]
- Mining \[= 0.03 \times 10^6 \text{ km}^2 = 0.02\% \]
Land Conversion and Degradation

- Total land converted by humans since prehistoric times
  \[ \approx 30 \times 10^6 \text{ km}^2 = 20\% \text{ of land surface.} \]
  3/4 of this occurred since 1700 AD.

  Example: Forests & grasslands to croplands:
  \[ 15 \times 10^6 \text{ km}^2 = 10\% \]

- Total land degraded \[ \approx 40-50 \times 10^6 \text{ km}^2 = 30\%. \]

  Example: Forests & grasslands to desert:
  \[ 15 \times 10^6 \text{ km}^2 = 10\% \]

- Current desertification rate \[ \approx 60,000 \text{ km}^2/yr \]
Humans have preferentially converted the most useful, most fertile biomes. Inhospitable biomes remain largely intact.
Deforestation
Deforestation

• About half of the world’s original forests have disappeared.

• According to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat,
  – Subsistence farming - 48%
  – Commercial agriculture - 32%
  – Logging - 14%
  – Fuel wood removals - 5%

• According to the Intergovernmental Panel on Climate Change, deforestation could account for up to one-third of total anthropogenic carbon dioxide emissions.
Deforestation in U.S.
Tropical Deforestation

- Current deforestation rate 100,000 - 200,000 km\(^2\)/y
  - Amazon basin: total forest area = 6 \times 10^6 km^2; today losing 1.5 \times 10^4 km^2 per year
  - Tropical forest declining 1-2% per year (annual loss the size of Pennsylvania)

- Why special concern for tropical deforestation:
  1. Relatively irreversible process, long recovery time
  2. Forests are essential to people outside market economy
  3. High levels of biological diversity
Deforestation Effects

• According to the Intergovernmental Panel on Climate Change deforestation, mainly in tropical areas, could account for up to one-third of total anthropogenic carbon dioxide emissions. ([http://www.ipcc.ch/](http://www.ipcc.ch/))

• Reduces soil cohesion, leading to erosion, flooding and landslides

• Increased runoff

• Decreased evapotranspiration, decreasing atmospheric moisture, changing precipitation levels

• Decline in biodiversity
## Top 10 Most Endangered Forests 2011

<table>
<thead>
<tr>
<th>Endangered forest</th>
<th>Region</th>
<th>Remaining habitat</th>
<th>Predominate vegetation type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indo-Burma</td>
<td>Asia-Pacific</td>
<td>5%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>New Caledonia</td>
<td>Asia-Pacific</td>
<td>5%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Sundaland</td>
<td>Asia-Pacific</td>
<td>7%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Philippines</td>
<td>Asia-Pacific</td>
<td>7%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Atlantic Forest</td>
<td>South America</td>
<td>8%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Mountains of Southwest China</td>
<td>Asia-Pacific</td>
<td>8%</td>
<td>Temperate coniferous forest</td>
</tr>
<tr>
<td>California Floristic Province</td>
<td>North America</td>
<td>10%</td>
<td>Tropical and subtropical dry broadleaf forests</td>
</tr>
<tr>
<td>Coastal Forests of Eastern Africa</td>
<td>Africa</td>
<td>10%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Madagascar &amp; Indian Ocean Islands</td>
<td>Africa</td>
<td>10%</td>
<td>Tropical and subtropical moist broadleaf forests</td>
</tr>
<tr>
<td>Eastern Afromontane</td>
<td>Africa</td>
<td>11%</td>
<td>Montane grasslands and shrublands</td>
</tr>
</tbody>
</table>
REDD

- United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries
- Started September 2008 to assist developing countries prepare and implement national REDD+ strategies, and builds on the convening power and expertise of the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP).
- Programme currently supports 44 partner countries spanning Africa, Asia-Pacific and Latin America, of which 16 are receiving support to National Programme activities.

http://www.un-redd.org/
Desertification

- **Desertification** = the process of fertile land transforming into desert typically as a result of deforestation, drought or improper/inappropriate agriculture
- Drylands occupy approximately 40-41% of Earth’s land area
- About 10–20% of drylands already degraded
- Desertification between 6 and 12 million km²
- 1–6% of the inhabitants of drylands live in desertified areas, and a billion people are under threat from further desertification.
Desertification Causes

- Over cultivation of desert lands, leading to loss of nutrients in the soil
- Improper irrigation practices result in salt buildup in soils and depletion of aquifers.
- Erosion and runoff decreases vegetation cover.
- Overgrazing removes this vegetation causing erosion and loss of topsoil.
Desertification

Desertification Vulnerability

VULNERABILITY
Low
Moderate
High
Very High
Not vulnerable

OTHER REGIONS
Dry
Cold
Humid
Ice/glacier

Miller Projection
SCALE 1:100,000,000

KILOMETERS
0 500 1,000 3,000 6,000 9,000 12,000 15,000 18,000

Country boundaries are not authoritative.
Desertification in Asia and Africa
Soil Degradation

- Soils determine fertility and productivity of land. They are...
  - the source of nutrients and water
  - the matrix for reactions that make nutrients available
  - the anchor to support plants

- Soils are typically 1-2 m deep (but can be much less or more)

- It takes 200 - 1000 years to form 1 cm of soil

- Two main types of damage:
  - topsoil loss
  - chemical changes

- Premodern erosion rate 5 Gt soil/yr; modern 30 Gt soil/yr
  - natural forest ~ 10 t/km² y
  - natural grasslands ~ 100 t/km² y
  - cropland ~ 2000 t/km² y
  - construction sites ~ 20,000 t/km² y
Why U.S. Farms in Midwest are so Vulnerable to Summer 2012 Drought in U.S.

• Monocultures…mostly corn and soybeans.
  – Possible solution - diversification

• Corn and soybeans are annuals with shallow roots, bred for rapid summertime growth. They cannot withstand a bad season.
  – Possible solution - shifting to other farming systems…more perennial crops and deep-rooted grasses and trees

• Industrial farming have depleted organic matter in soil, reducing ability to absorb and store moisture.
  – Possible solution - no-till agriculture and organic farming practices can restore the health of the soil, and greatly improve the resilience of crops to extreme weather.
Why U.S. Farms in Midwest are so Vulnerable to Summer 2012 Drought in U.S.

- Commodity agriculture inefficient – Most of American corn and soybeans are used to feed animals (where cattle require 30 pounds of grain to add one pound of boneless beef) and produce ethanol rather than feed people directly.
  - Possible solutions – replace some of the corn and soybeans with more resilient grains, fruits, and vegetables that go directly into the human diet and with grasslands to feed animals and create cellulosic biofuels would feed more people.
Impacts of Water Use on Aquatic Ecosystems

- Aquatic ecosystems are among the most degraded by human activities.
- 1/3 of aquatic species are threatened/endangered
- Human activities cause changes in water flow, timing, temperature, nutrients, sediments.
- Bad synergies with pollution, grazing, climate change
- Example of synergy: riparian habitat degraded by grazing, loses water retention capacity + dried out by water diversion upstream
Aral Sea

- Formerly world’s 4th-largest inland sea (1100 km³), on Kazakhstan-Uzbekistan border.
- In 1940s, the two main rivers feeding the Aral Sea were diverted for agriculture (cotton and cereals) in the desert.
- By 1960 the sea began to shrink; in 2009 it is 9% of original surface area.
- Remaining fragments are >2x saltier than the ocean. The dry seabed is a wasteland of salt and toxic chemicals.
- Restoration is being discussed but will be extremely difficult.
Salton Sea

- Located in desert basin 300 feet below sea level with no outflow.
- Current sea formed in 1905 due to levee breach on Colorado River.
- Salton Sea now sustained by agricultural runoff.
- Important for migratory birds & tourism.
- Sea suffering ongoing degradation:
  - Fertilizer & pesticide runoff
  - Increasing salinity
Delta smelt: example of ecosystem impacts

- Wetland, river, and lake ecosystems are among the most affected by humans.
- The Delta smelt is a small fish endemic to the Sacramento Delta. In the 1980s and 1990s, water withdrawals for agriculture increased the Delta’s salinity and devastated fish populations.
- It was listed as an endangered species in 1993. The Sacramento Delta is “critical habitat” for the smelt, and protection of the Delta is therefore required by law.
- However, the agriculture fed by Delta water is economically and socially valuable, giving rise to a legal battle.
Biodiversity
Biodiversity

- **Biodiversity** is the degree of variation of life forms within a given species, ecosystem, biome, or an entire planet. Biodiversity is a measure of the health of ecosystems.
- Biodiversity is much harder to measure than the other resources we’ve discussed.
- Estimates of human impact on biodiversity are highly variable.
- However, there is broad agreement that humans are having a profound effect - it has been called the “6th mass extinction.”
Ways to Describe Biodiversity

- Biodiversity can be defined at several different scales:
  
  **Genetic diversity**
  *Number of gene variants in a population*

  **Species diversity**
  *Number of different species in an ecosystem*

  **Ecosystem diversity**
  *Number of different ecosystem types*

- Diversity at one level impacts diversity at the other levels: for example, loss of ecosystems causes loss of species.

- We tend to focus on *species diversity* because it is easier to quantify and understand.
Biodiversity Distribution

• Biodiversity depends on
  – Temperature
  – Precipitation
  – Altitude
  – Soils
  – Geography
  – presence of other species.

• Diversity greater in the tropics and lower in polar regions
Diversity Calculations

Diversity (of anything) is related to:

- Richness: how many different types are there?
- Evenness: how well distributed are the different types?

Ecosystem 1

Richness = 3
Evenness ($\hat{D}$) = 0.34

Ecosystem 2

Richness = 3
Evenness ($\hat{D}$) = 0.66

\[ \hat{D} = 1 - \sum_{i=1}^{S} p_i^2 \]

where \( \hat{D} \) = index of diversity;
\( s \) = number of species;
\( p_i \) = fraction of all individuals in the \( i \)th species
Number of Species

- According to the Global Taxonomy Initiative and the European Distributed Institute of Taxonomy,
  - 10–30 million insects (including 0.9 million we know today)
  - 5–10 million bacteria
  - 1.5 million fungi (including 0.075 million we know today)
  - 1 million mites
  - The number of microbial species is not reliably known
**Undiscovered Species Chart**

- **Discovered species:**
  - Insects: 950000
  - Plants: 270000
  - Arachnids: 75000
  - Mushrooms: 72000
  - Mollusca: 80000
  - Vertebrates: 56000
  - Algae: 40000
  - Protozoa: 30000
  - Crustaceans: 75000
  - Other invertebrates: 120000

- **To discover:**
  - Insects: 8950000
  - Plants: 380000
  - Arachnids: 740000
  - Mushrooms: 470000
  - Mollusca: 250000
  - Vertebrates: 61000
  - Algae: 400000
  - Protozoa: 210000
  - Crustaceans: 180000
  - Other invertebrates: 400000
Threats to Biodiversity

- Habitat loss and habitat fragmentation (e.g. pandas, tigers, lemurs) - most important
- Pollution (e.g. bald eagles and DDT)
- Hunting / overharvesting (e.g. wolves, passenger pigeons)
- Invasive species (e.g. dodo and egg-eating rats)
- Introduced diseases (e.g. chestnut blight)
- Climate change:
  - directly, through changing T or precipitation
  - indirectly, by influencing other factors above

Note that these effects all relate to the other human impacts.
Extinctions and Threatened Species

- There have been nearly 1,000 recorded extinctions since 1600, and doubtless many more unrecorded ones.
- There are 15,000 threatened species (1% of the total) on the International Union for Conservation of Nature, IUCN, Red List (http://www.iucnredlist.org/). This is a lower limit for the real total.
Which taxa are most vulnerable?

- Amphibians
- Mammals
- Birds
- Gymnosperms (conifers & kin)

Why? We don’t exactly know...

### Data from IUCN (1994), cited in Botkin & Keller
A species-area relationship (SAR) describes how the cumulative number of species increases as land area increases. It is usually concave, and often fits the curve $S = cA^z$ (where $c$ and $z$ are constants for that system).

Species-area relationships allow us to predict total species in an area (or species lost to habitat destruction) without counting them.
Current vs. Historical Extinction Rates

Extinction rates are very hard to measure (especially from fossils), but we estimate that

**Background rate =**

\[
\frac{1 \text{ extinction}}{(10^6 \text{ species} \cdot \text{year})}
\]

**Current rate =**

\[
\frac{1 \text{ extinction}}{(10^4 \text{ to } 10^5 \text{ species} \cdot \text{year})}
\]

*An increase of 10 to 100 times.*

Several prominent biologists (Edward Wilson and Peter Raven) have suggested that >50% of species will disappear by 2100.
Relationships

GLOBAL

REGIONAL

LOCAL

Human well-being and poverty reduction
- BASIC MATERIAL FOR A GOOD LIFE
- HEALTH
- GOOD SOCIAL RELATIONS
- SECURITY
- FREEDOM OF CHOICE AND ACTION

Indirect drivers of change
- DEMOGRAPHIC
- ECONOMIC (e.g., globalization, trade, market, and policy framework)
- SOCIOPOLITICAL (e.g., governance, institutional and legal framework)
- SCIENCE AND TECHNOLOGY
- CULTURAL AND RELIGIOUS (e.g., beliefs, consumption choices)

Ecosystem services
- PROVISIONING (e.g., food, water, fiber, and fuel)
- REGULATING (e.g., climate regulation, water, and disease)
- CULTURAL (e.g., spiritual, aesthetic, recreation, and education)
- SUPPORTING (e.g., primary production, and soil formation)

Direct drivers of change
- CHANGES IN LOCAL LAND USE AND COVER
- SPECIES INTRODUCTION OR REMOVAL
- TECHNOLOGY ADAPTATION AND USE
- EXTERNAL INPUTS (e.g., fertilizer use, pest control, and irrigation)
- HARVEST AND RESOURCE CONSUMPTION
- CLIMATE CHANGE
- NATURAL, PHYSICAL, AND BIOLOGICAL DRIVERS (e.g., evolution, volcanoes)

LIFE ON EARTH - BIODIVERSITY

Strategies and interventions

Source: Millennium Ecosystem Assessment
International Agreements

• Convention on Biological Diversity
  http://www.cbd.int/

• Convention on International Trade in Endangered Species
  http://www.cites.org/

• Convention to Combat Desertification
  http://www.unccd.int/en/Pages/default.aspx

• Ramsar Convention on Wetlands
  http://www.ramsar.org/cda/en/ramsar-home/main/ramsar/1_4000_0

• Convention on Migratory Species
  http://www.cms.int/

• Millennium Ecosystem Assessment
Summary Notes

What is Earth’s current population?
7.0 billion, increasing 1.1% per year

What do we mean by $I = PAT$?

$Impact = Population \times Affluence \times Technology$

Humans have transformed what fraction of Earth’s surface?

About 20%; nearly all of the arable land

What is NPP? What fraction of it do humans intercept?

$Net\ primary\ production;\ 30\text{-}40\%$

What two variables determine the distribution of biomes?

$Precipitation\ and\ temperature$
Summary Notes (cont.)

How much of available runoff do humans use?
More than 50%

What is the biggest global water use?
Agriculture

Which ecosystem types have been altered the most?
Wetlands, riparian, many types of forest

By what factor has the extinction rate increased?
10 to 100 times

How many species are there?
2-10 million