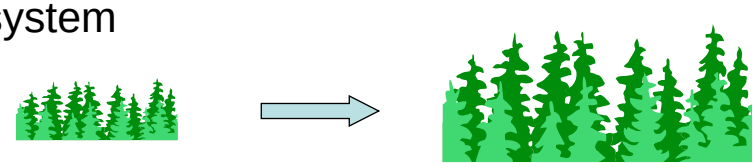
The Flow of Energy: *Primary Production*

***What we need to learn*:**

- What is ***primary production***, and how is it measured?
- How much of the sun's energy is assimilated by plants?
- How are ***primary*** and ***ecosystem productivity*** related?
- How are ***production***, ***standing crop***, and ***turnover rate*** related?
- What limits primary production?
- How does primary production vary among the world's ecosystems?

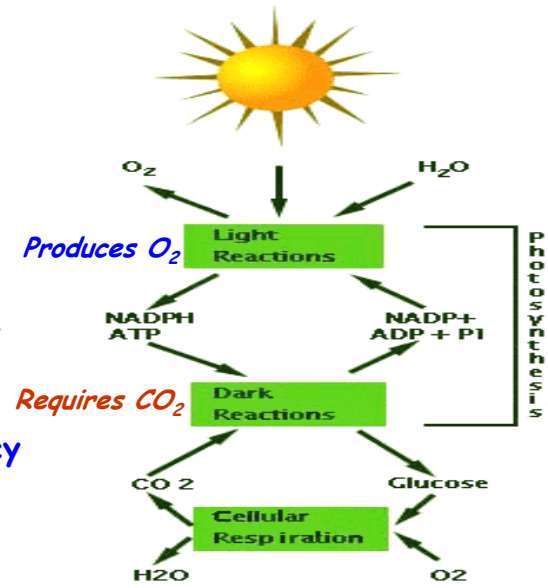
The Process of Primary Production

- **Production** is the creation of new organic matter
- **Primary production** is production of new organic matter by ***autotrophs***
- Over time, primary production results in the addition of new plant biomass to the system



Photosynthesis Requires Light Energy

(See primer on photosynthesis)



On Land, net efficiency

~ 0.01 - 3%

In Water, net efficiency

~ 0.01 - 1%

Definitions

* **Gross Primary Production = GPP**

  GPP = All CO_2 fixed by the plant in photosynthesis.

* **Respiration = R**

  R = CO_2 lost from metabolic activity

  R_p = Respiration by Plants
  R_h = Respiration by Heterotrophs
  R_d = Respiration by Decomposers

* **Net Primary Production = NPP**

  $NPP = GPP - R_p$

* **Net Ecosystem Production = NEP**

  $NEP = GPP - (R_p + R_h + R_d)$

Measuring Primary Production

1. **Measure the rate of photosynthesis**

   $CO_2 + H_2O \;\; ===> \;\; C_6H_{12}O_6 + O_2$

   – ***a).*** measure the CO_2 used (^{14}C)

   – ***b).*** measure the O_2 produced

   – estimates ***GPP*** (Gross Primary Production, total energy "fixed")

2. **Measure the rate of formation of new plant matter**

   – final plant biomass minus initial

   – estimates ***NPP*** (Net Primary Production = total energy fixed - metabolic costs, herbivory, etc.)

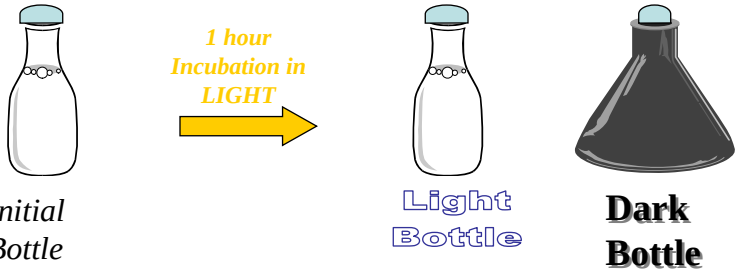
   – Respiration is the reverse process:

   $C_6H_{12}O_6 + O_2 \;\; ===> \;\; CO_2 + H_2O$

Light-Dark Bottle Method

1. **Fill all bottles with sample water.**

2. **Measure initial O_2 , incubate samples in the light.**



3. **Measure final O_2 in light and dark bottles.**

Initial Bottle = ***8 mg O_2/L***

Light Bottle = **GPP & Resp**
= **10 mg O_2/L**

Dark Bottle = **Resp**
= **5 mg O_2/L**

(Light - Initial) = (10 - 8) = 2 mg/L/hr = GPP - R = NPP

(Initial - Dark) = (8 - 5) = 3 mg/L/hr = Respiration, R

(Light - Dark) = (10 - 5) = 5 mg/L/hr = NPP + Resp = GPP

Production, Turnover, and Standing Crop

- ***Production*** is reported as the formation rate of new organic matter, per unit area of earth, per unit of time:
  - calories / m^2 / year (energy)
  - grams / m^2 / year (organic matter)
- ***Standing crop*** is the amount of organic matter in a given area at a specific time
  - cal / m^2 (energy)
  - g / m^2 (organic matter)
- In managing a forest, should we be more interested in the forest's production, or its standing crop? ***What variable must we consider?***

Time!

- $\frac{\text{Standing crop}}{\text{Production}} =$

- $\frac{(g / m^2)}{(g/m^2/year)} = 1 / (1/year)$

  $= year$

- $\frac{\text{Stock}}{\text{Rate}} =$ ***Measure of time:***

  (Residence Time or Turnover Time)

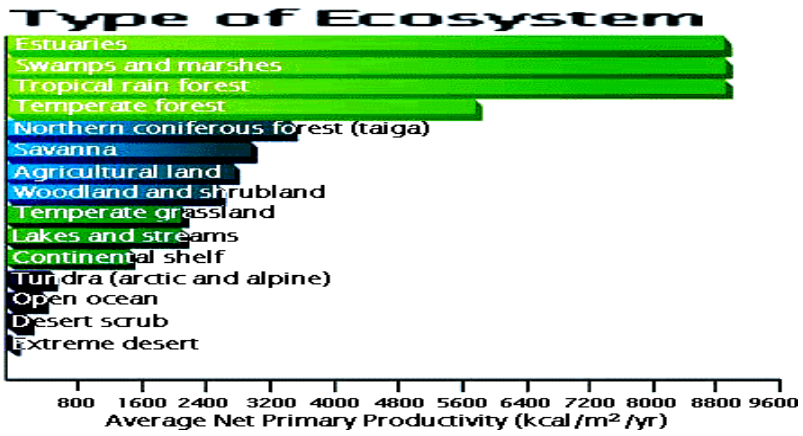
Take-Home Message #1:

"Time affects everything – always consider time."

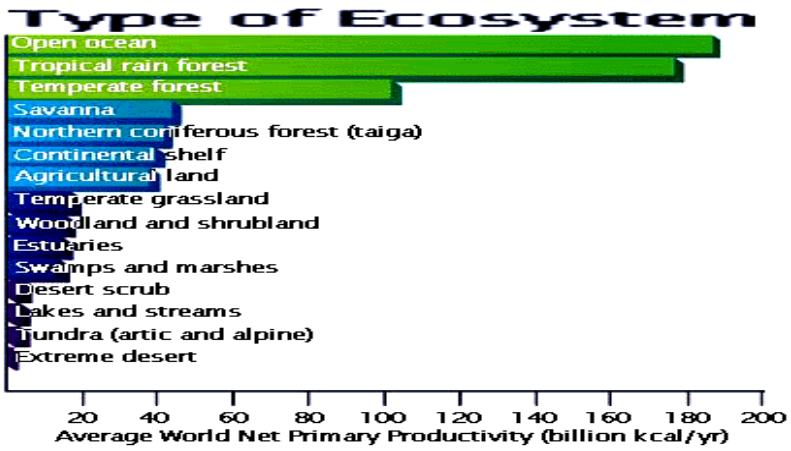
Primary Production of the World's Ecosystems

- World ecosystems vary widely in productivity.
- **The most productive systems** (by unit area) are estuaries, swamps and marshes, tropical rain forests, and temperate rain forests.
- **In terms of global NPP**, the most productive systems are open oceans, tropical rain forests, savannas, and tropical seasonal forests.

Productivity per unit area (m^2)



Total Productivity (global)



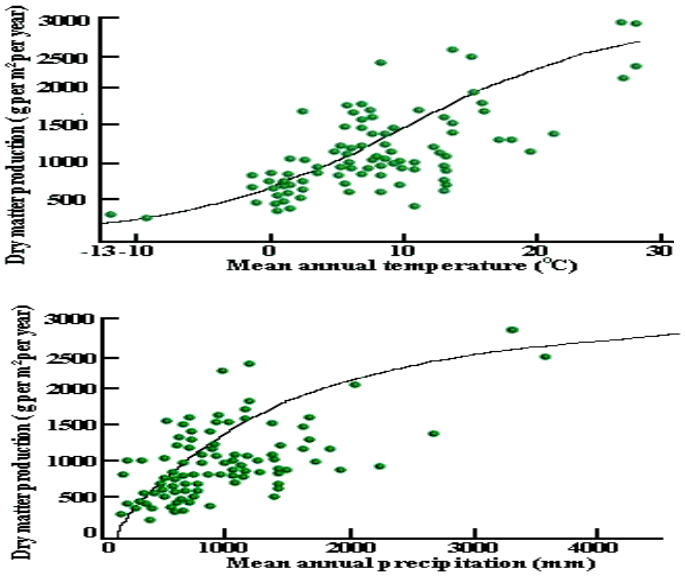
What Determines Ecosystem Productivity?

- Climate and nutrients determine ecosystem productivity.
- In general, ***NPP increases with precipitation and temperature.***

- Areas low in nutrients, such as the open ocean, have low NPP per unit area.

For any given temperature or precipitation there is a large spread of production values – Why?

NUTRIENTS!



Summary (so far…)

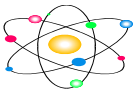
- Primary production is the creation of new organic matter by plants and other autotrophs.
- Primary production can be quantified by measuring the rate of the photosynthetic reaction.
- GPP is the total organic matter synthesized. NPP < GPP due to metabolic costs of autotrophs.
- Production varies among ecosystems due to climate and nutrient availability.

The Flow of Energy: Higher Trophic Levels

We wish to know:

- **With what efficiency is energy converted between trophic levels?**
- **What is *assimilation efficiency*, *net production efficiency*, and *ecological efficiency*?**
- **What are pyramids of numbers, biomass, and energy?**
- **How much energy is available to humans, and how much do we use?**

Energy Transfers to Higher Trophic Levels

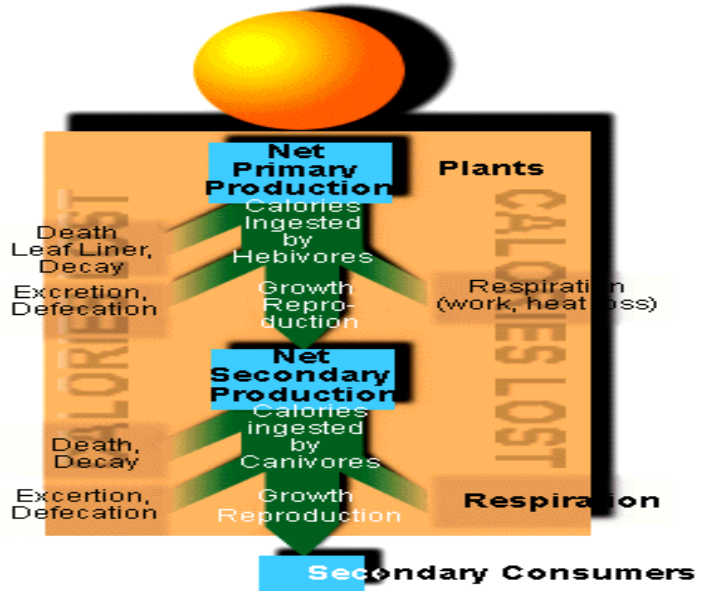


What happens to NPP?

On average, it is consumed. Some is stored in sediments (coal, oil).

Energy is released in this consumption, and metabolic work is done as cellular respiration converts energy stored in chemical bonds into heat. This energy is lost for the next trophic level.

Energy Flows and Losses



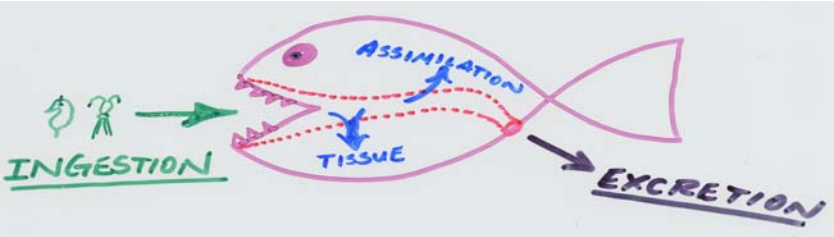
Principles of Energy Flow

As energy passes from trophic level to trophic level:

- Only a fraction of the energy available to one trophic level is transferred to the next trophic level. The rule of thumb is ~10%, but this can vary from 1 - 15%.
- Typically the numbers and biomass of organisms decreases as one ascends the food chain. This is called a “pyramid”.

1. "Assimilation Efficiency"

= (Assimilation / Ingestion)



Assimilation = (Ingestion) – (Excretion)

Assimilation Efficiency

= 15 – 50 % for plant food

= 60 – 90 % for animal food

2. "Net Production Efficiency"

= (Production / Assimilation)

Production = (Growth + Reproduction)

- For plants, net production efficiency
  = (NPP / GPP) = 30-85%
- For invertebrates = 20% on average
- For vertebrates = 2% on average ***WHY ?***

3. "Ecological Efficiency"

= consumer production / prey production

For example,

= Fox production / Rabbit production

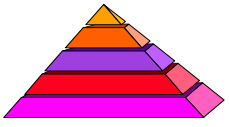
= [(10 kg/yr) / (100 kg/yr)] * 100 **= 10 %**

* Ecological efficiency ranges from ~1 to 15 %

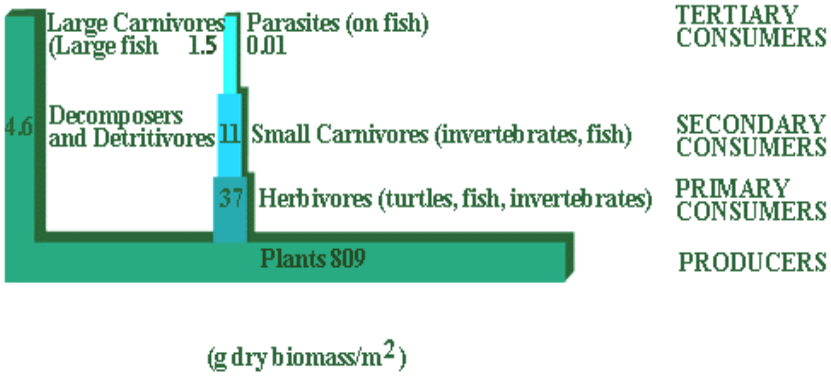
* This sets the absolute number of trophic levels in a food web

Pyramids of Numbers, Biomass, and Energy

- Because energy is "used up" by the metabolic activities of organisms, the amount of energy available to the next trophic level (e.g., foxes) is less than the amount that entered the trophic level below (e.g., hares).
- In general, this lower amount of energy available leads to a decrease in standing crop biomass or numbers of organisms as one proceeds to higher trophic levels.

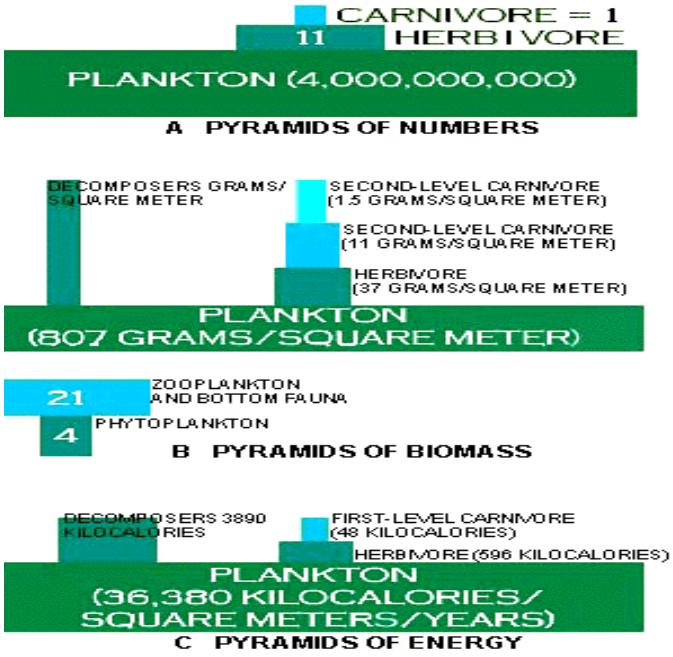


A Typical Pyramid of Biomass



Pyramids -- *complications* and *exceptions*

- Complications: pyramids of numbers might be ***steep*** if the predators are much larger than their prey, - or -, they might be ***inverted*** if large plants have numerous insect grazers.
- Exceptions: pyramids of biomass might be ***inverted*** if a lower trophic level has a much higher turnover rate than a higher trophic level.
- **Pyramids of energy can never be inverted.**



Residence Time of Energy

- R_T= (energy in biomass/ net productivity)

Ecosystem	NPP	Biomass	R_T
	(g/m²/yr)	*(g/m²)*	*years*
Tropical Rainforest	2,000	45,000	22.5 yrs
Boreal Forest	800	20,000	25.0 yrs
Temperate Grassland	500	1,500	3.0 yrs
Lakes	500	20	15 days
Open Ocean	125	3	9 days

World NPP & Human Consumption

- **World NPP** is ~ 224.5 Pg/yr of organic matter.
- 1 pedagram = 10^{15} g = 10^{9} metric tonnes
  (1 metric tonne = 1,000 kg)

- **Terrestrial NPP > Aquatic NPP** *(despite oceans covering 70% of earth's surface)*

The Human Use of Global Production

Source	**NPP used & co-opted (Pg)**
Cultivated land	15.0
Grazing Land	11.6
Forest land	13.6
Human-occupied areas	0.4
Sub-total terrestrial	*40.6*
Fisheries	2.0
Total	42.6
% terrestrial NPP co-opted (40.6/132.1)	**30.7 %**

The High Calculation

Source	Amount (Pg)
Previous terrestrial total	40.6
Decreased NPP in agriculture	9.0
Conversion forest to pasture	1.4
Desertification	4.5
Loss to settlement	2.6
Sub-total terrestrial	**58.1**

% Terrestrial co-opted (58.1/149.8) **38.8 %**

% Total NPP co-opted (60.1/224.5) **24.8 %**

World NPP & Human Consumption

- **Middle estimate = 40.2 Pg (30.7%)** annually (direct and co-opted use as food, fiber, fuel, timber)

- **High estimate = 58.1 Pg (39%)** annually (direct use, co-opted NPP, and forgone NPP)

Implications of Human Co-option of NPP:

1. **Human use of marine productivity is small**
2. **On land, 1 species commands almost 40% of NPP**
3. **Consequences include environmental degradation, species extinctions, altered climate**
4. **What is the human carrying capacity of the planet?**

Being Alive - vs.- **Having a life**

Take-Home Message #2:

"Ecological efficiency will get us in the end."