Terrestrial Carbon Cycle:

Allocation, Decomposition, Nutrient Cycling, and Sink Processes

Please read:

- Schulze, E.-D., 2002. "Carbon Turnover." In: *Plant Ecology*. Springer. p. 427-438.
- Norby, R. J. et al (2010), CO_2 enhancement of forest productivity constrained by limited nitrogen availability, *Proc. Nat. Acad. Sci*, 107, 19368–19373.
- Pan, Y. et al (2011a), Age structure and disturbance legacy of North American Forests. Biogeosciences 8, 715-732

Carbon Allocation:

What happens to photosynthate (glucose) after it is formed in chloroplast?

- Some is consumed to drive biosynthesis processes in leaf
- Some is stored in easily-available form for later
- Some stored photosynthate is transported to other parts of the plant (roots, stems) to be used there for maintenance and growth
- Relative allocation to leaves, stems, and roots depends on resource needs
  - Plant is shaded (light-limited): grow more stem
  - Water or nutrient limited: grow more roots
  - Fat and happy: grow more leaves
- Question: Where does carbon & nitrogen come from when it' s time to grow new leaves in spring?

Plant Respiration

Gross Primary Production – Plant respiration = Net Primary Production

$GPP - R_a = NPP$

$GPP - R_m - R_g = NPP$

$R_m = f(N, \text{temperature}, O_2)$ Maintenance respiration

R_g - growth respiration, involves construction costs of building new tissues f(new growth)

$GPP - R_{leaf}(m + g) - R_{stem}(m + g) - R_{root}(m + g) = NPP$

Allocation and respiration processes occur simultaneously

Factors controlling plant respiration

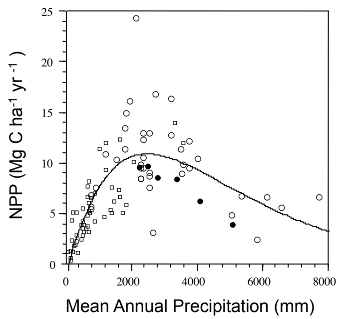
$NPP = GPP - R_a$

1. Tissue N -- protein turnover; 6% replaced daily
2. Temperature -- increased protein and membrane turnover at higher temperatures

GPP and R_a generally related, so NPP and GPP are proportional

However, at high temperatures, GPP may be maintained or inhibited, while R_{plant} increases. NPP/GPP decreases.

Water Controls NPP

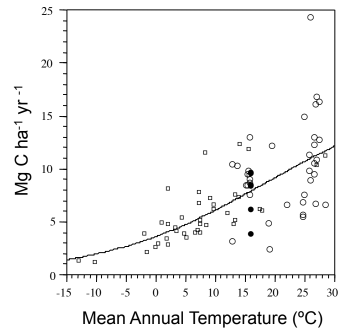


At global scale,
ppt and T are strongly correlated with NPP

Water increases plant growth in drier ecosystems. Also increases decomposition and nutrient cycling.

In extremely wet climates, ppt can limit NPP by decreasing light or nutrient availability

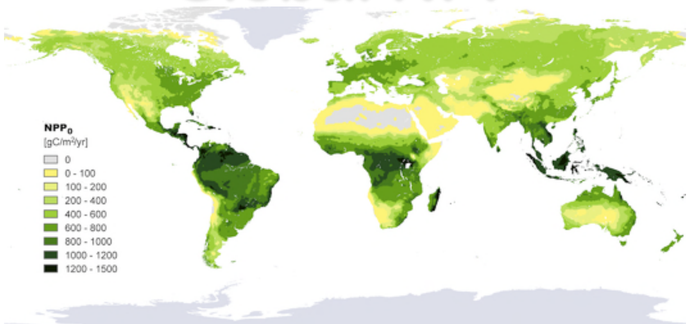
Temperature Controls NPP



Annual mean temperature is related to growing season length

Temperature stimulates decomposition and nutrient cycling

Global NPP

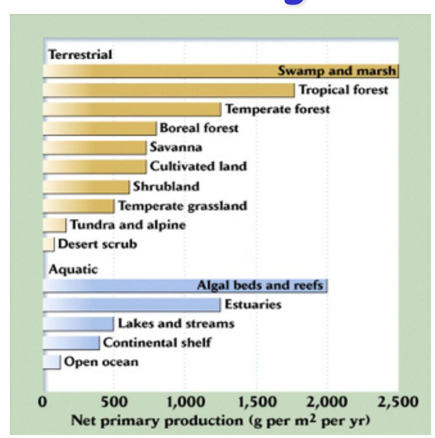


Haeberl et al, 2007, PNAS

"Potential" NPP, not actual because management effects, agriculture, irrigation, urbanization, and other land use not accounted for

Latitude effects (growing season, decomp); Aridity effects

NPP by "Biome"



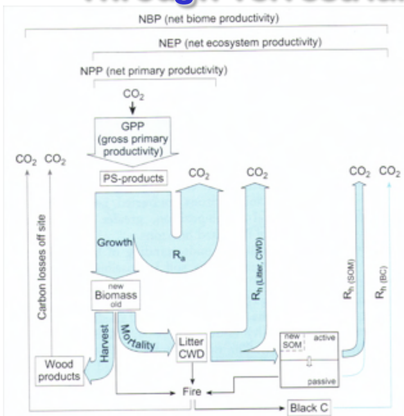
Note that these are per unit area!

Forests & grasslands dominate because of larger areas

Coral reefs are like forests!

Flows of Fixed Carbon

Through Terrestrial Ecosystems



$NPP = GPP - R_a$

$NEP = GPP - R_a - R_h$

$NEP = NPP - R_h$

$NBP = NEP - \text{disturbance}$

$NBP = NEP - \text{harvest} - \text{fire}$

NBP is what the atmosphere "sees" it is equal to carbon accumulation within the ecosystem

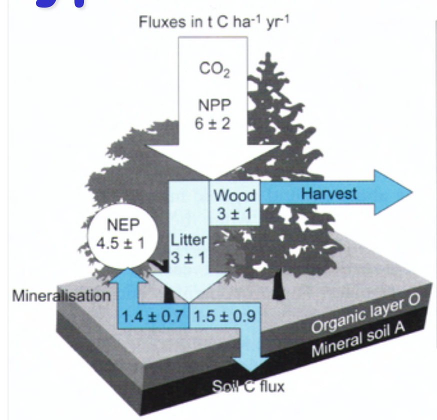
Carbon "Pools"

by "Biome" (Schulze 2002)

Ecosystem	Biomass (kg C m^{-2})	NPP (kg C m^{-2} a^{-1})	Leaf litter (kg C m^{-2} a^{-1})
Tropical rainforest	20–32	3–10	0.5–1.4
Temperate deciduous forest	5–30	0.2–1.2	0.1–0.6
Temperate coniferous forest	15–75	0.4–1.3	0.1–0.6
Boreal coniferous forest	8–10	0.3–0.4	0.1–0.5
Savannah	1–2	0.4–0.6	0.1–0.4
Grassland	0.2–2.2	0.1–1.0	<0.1–1.0
Agricultural land	0.5	0.3–0.5	0.1–0.2
Desert	0.2–3	<0.1–0.5	<0.1–0.2
Tundra	0.1–2	<0.1–0.2	<0.1

Vegetation type	Roots Total (kg m^{-2})	Fine roots Mass (kg m^{-2})	Fine roots Length m m^{-2}	Fine roots Root surface index (m^2 m^{-2})	Leaves or needles Mass (kg m^{-2})	Leaves or needles Leaf surface index (m^2 m^{-2})
Tropical rain forest	4.88	0.57	4.1	7.4	2.5	11
Temperate coniferous forest	4.40	0.82	6.1	11.0	1.3	9
Temperate deciduous forest	4.14	0.78	5.4	9.8	0.4	7
Boreal forest	2.92	0.60	2.6	4.6	1.8	11
Shrub vegetation	4.82	0.52	8.4	11.6	0.4	8
Savannah	1.40	0.99	60.4	42.5	0.9	3
Temperate grassland	1.56	1.51	112.0	79.1	0.6	3
Tundra	1.25	0.96	4.1	7.4	0.4	2
Desert	4.13	0.27	4.0	5.5	0.1	<1
Average	3.28	0.78				

Typical Carbon Flows



	MRT (years)
Litter	< 1 – 3
Wood	1 – 250
Managed forest	Mean: 80
Wood products	15 – 20
Organic layer	14 – 52
A horizon	70 – 170

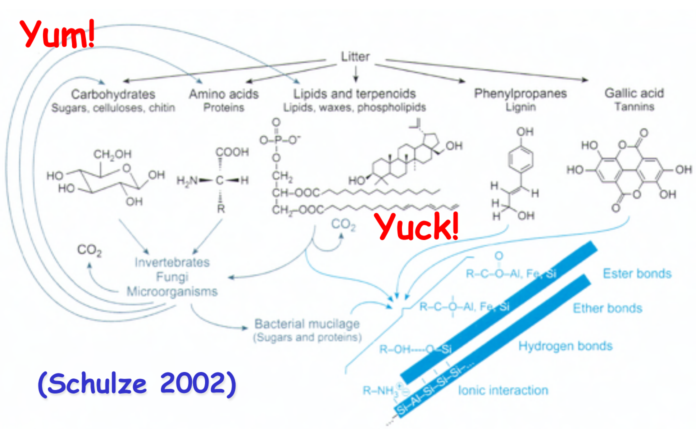
in a rapidly growing forest (Schulze 2002)

Decomposition

$$\frac{dC}{dt} = -k_{\max} \cdot C \cdot f(chemistry) \cdot f(temperature) \cdot f(water\ availability)$$

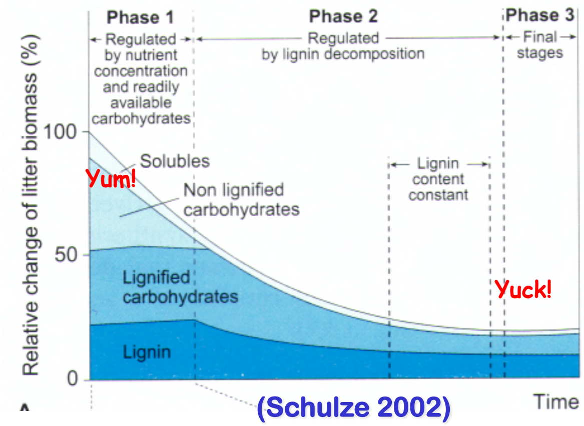
- k_{max} – maximum rate constant for litter or SOM loss under ideal conditions
- C – mass of litter at the beginning of time interval
- *f(chemistry)* – scalar describing the rate at which microbes degrade the plant material (typically a function of N, cellulose, lignin)
- *f(temperature)* – scalar describing sensitivity of microbes to temperature
- *f(water availability)* – scalar describing microbial response to soil/surface moisture

Litter Decomposition

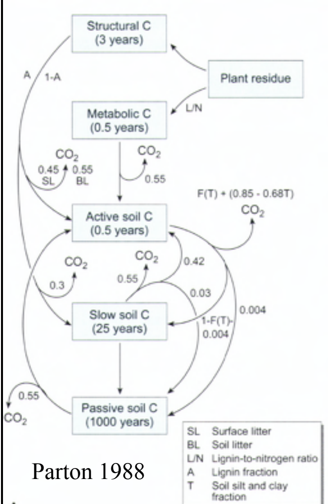


(Schulze 2002)

Litter Decomposition



(Schulze 2002)

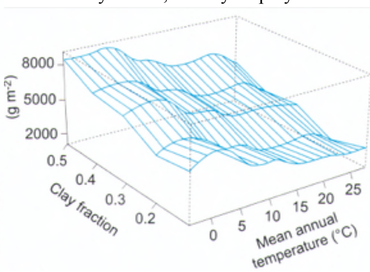


Parton 1988

CENTURY

Litter Decomposition and Soil Organic Matter Transformations

modeling approach for litter and soil organic matter dynamics, widely employed

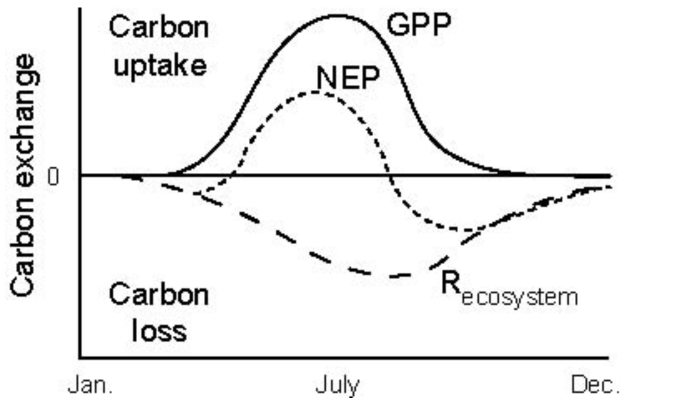


Global Terrestrial Ecosystem Fluxes

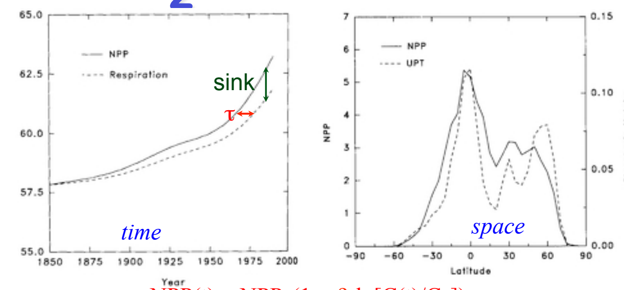
(1 Pg C = 10^{15} g C)

Concept	Acronym	Global Flux	Definition
Gross Primary Production	GPP	~100 –150 Pg C yr^{1}	Carbon uptake by plants during photosynthesis
Autotrophic Respiration	R_a	~ ½ of GPP	Respiratory loss by plants for growth or maintenance
Net Primary Production	NPP	~ ½ of GPP	GPP – R_a
Heterotrophic Respiration (on land)	R_h	~82% – 95% of NPP	Respiratory loss by the heterotrophic community (herbivores, microbes, etc.)
Ecosystem Respiration	R_a	~91% – 97% of GPP	$R_a + R_h$
Non-CO_2 Losses		~2.8 – 4.9 Pg C yr^{-1}	CO, CH_4, terpenes, dissolved inorganic and organic carbon, etc
Non-Respiratory CO_2 Losses (Fire)		~1.6 – 4.2 Pg C yr^{-1}	Combustion flux of CO_2
Net Ecosystem Production or Net Biome Production	NEP	~±2.0 Pg C yr^{-1}	Total carbon accumulation within the ecosystem

Seasonal Cycles



CO_2 Fertilization

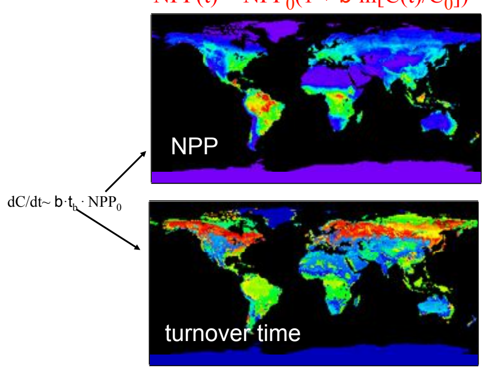


$NPP(t) = NPP_0(1 + \beta \ln[C(t)/C_0])$

- **Increasing plant growth (NPP) due to enhanced atmospheric CO_2**
- **Delayed increased respiration (residence time)**
- **Spatial pattern follows both NPP & residence time**

CO_2 Fertilization

$NPP(t) = NPP_0(1 + b \ln[C(t)/C_0])$

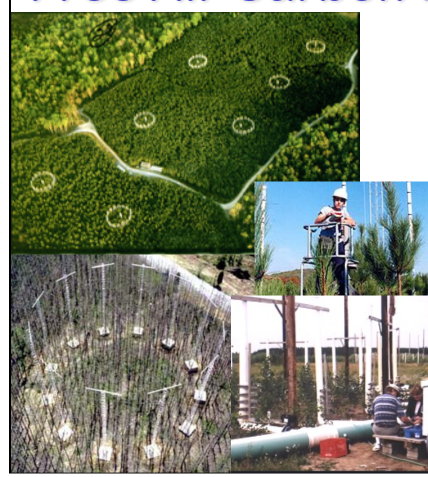


Distribution of NPP favors tropical CO_2 sink

Distribution of residence time favors boreal CO_2 sink

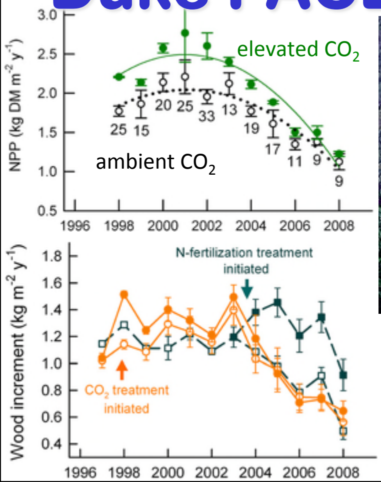
Net Primary Production and mean residence times of carbon determines source/sink potential of ecosystems

Free Air Carbon Enrichment (FACE)



- **Fumigation rings maintain steady levels of elevated CO_2 in canopies under changing weather conditions**
- **Control and replicated treatments test effects of CO_2, water, N, etc**

Duke FACE Results



- **Enhanced growth** in elevated CO_2
- **"Acclimitization"** after a few years

Norby et al (2010)

Nitrogen Fertilization

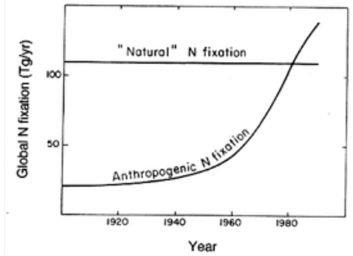
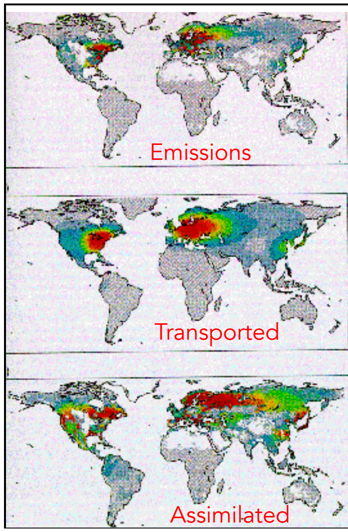


FIG. 8. Extent of human alteration of the global biogeochemical cycle of nitrogen. The "natural N fixation" line represents biological N fixation in natural terrestrial systems plus fixation by lightning; I assume that natural biological fixation has not changed recently, although it probably has declined due to land use change and increased N deposition. The "anthropogenic N fixation" line represents the sum of industrial N fixation for fertilizers, fixation during fossil fuel combustion, and fixation by leguminous crops (Smil 1991, Vitousek and Matson 1993). *Nitrogen biogeochemistry: The change reports the modern fractions for each source.*

- Atmospheric N_2 is triply-bound so chemically and **biologically inert**
- Natural N-fixation by **lightning and by specialized microbes**, linked to very tight N cycling in biosphere
- Manufacture of **fertilizers** uses energy to fix N
- **Combustion** burns air!

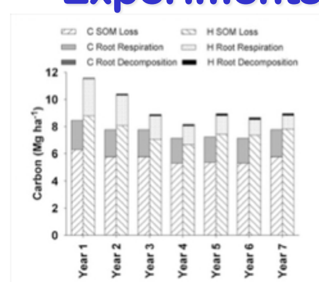
Atmospheric Deposition of Fixed N

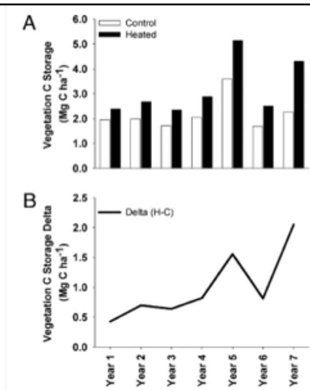


- **Combustion** burns air!
- $N_2 + O_2 \rightarrow 2\ NO$
- $(NO, NO_2) \rightarrow NO_3$
- Geography of **industry and westerly winds**
- N-limited forests take up **C:N at 200:1**

Townsend et al. 1996

Soil Warming Experiments

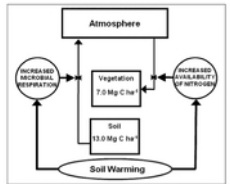




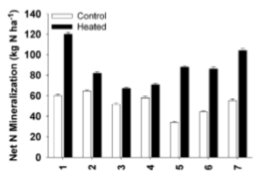
- Warming enhances ***both*** decomposition and vegetation carbon storage

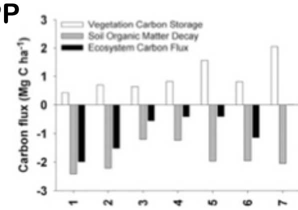
Soil warming, carbon–nitrogen interactions, and forest carbon budgets

Competing Carbon-Climate Feedbacks

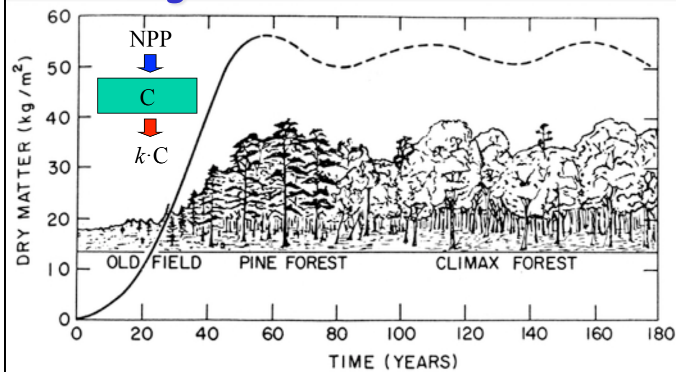


- Early C loss due to enhanced decay
- Enhanced N mineralization
- Later enhancement of NPP





Ecosystem Succession



Woodwell and Whittaker, 1968

$$\frac{dC}{dt} = NEP \cong NPP - R_h$$

Ecosystem Succession

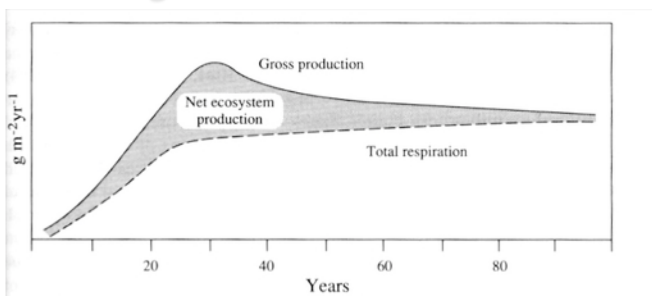
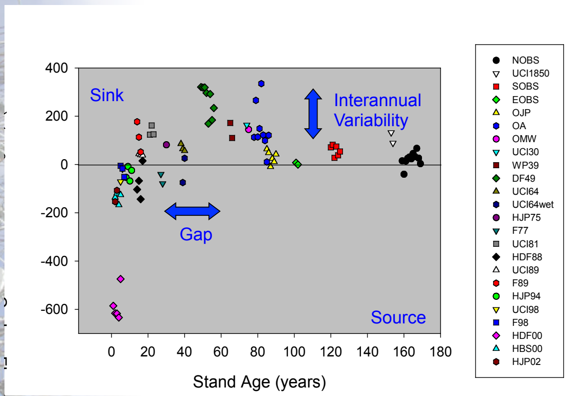


Figure 5.14 Generalized trends in primary production and respiration during ecosystem development. Modified from Odum (1969).

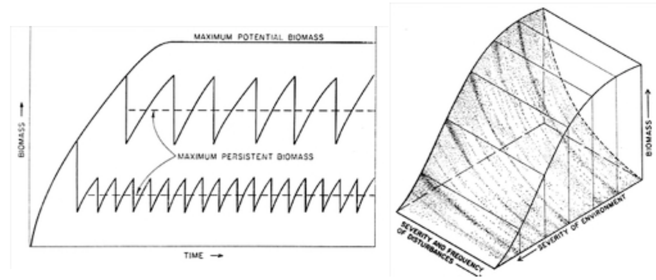
Disturbance and Recovery

Planted	2000	1988	1949
Height (m)	0.8	3-8	30-35

Fluxnet-Canada Annual Carbon Budgets



Disturbance and Steady State



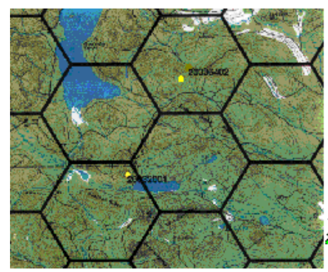
At a regional scale, patches of terrestrial ecosystems are always in different stages of recovery from disturbance. If the disturbance regime is constant, then the distribution of different successional states of ecosystems will remain constant.

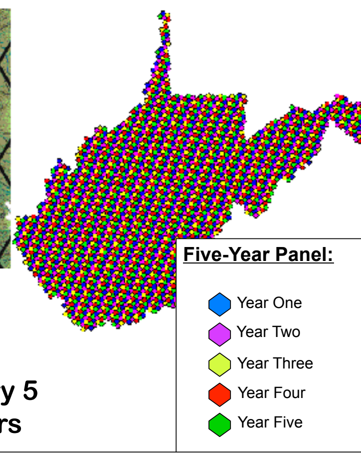
Reichle, 1974

Forest Inventory Sampling

USDA Forest Service measures hundreds of thousands of plots!

USDA Forest Service FIA Plots



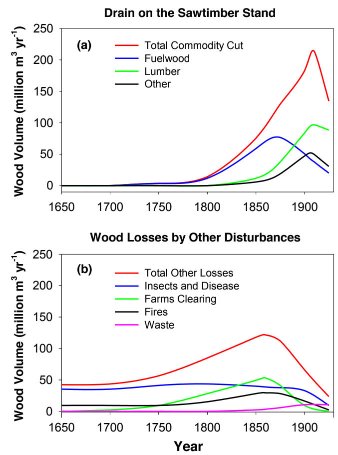


- **6000 acre grid cells**
- **1 plot per grid cell**
- **>800K plots**
- **each plot visited every 5 (east) or 10 (west) years**

Disturbance Patterns

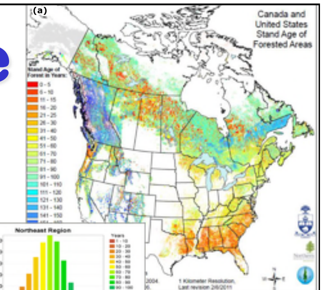
Pan et al (2011a)

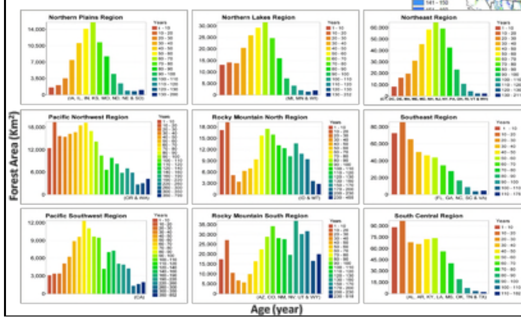
- Reconstructed clearing, fuelwood, and pulp & paper production in North America over 300 years
- Fuelwood and farm clearing peaked around 1850
- Lumber and paper production peaked about 1900



Disturbance Patterns

Pan et al (2011a)





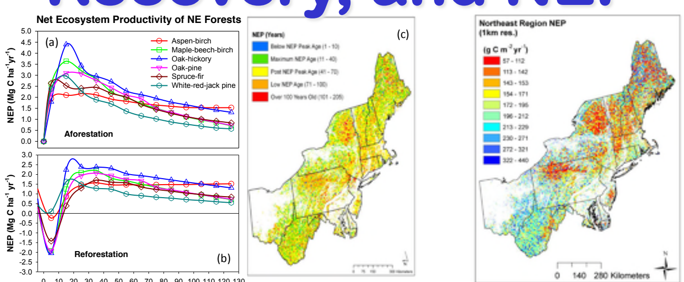
PNW and SE forests are young

NE forests are intermediate

Canadian patterns are complicated!

BC forests are old

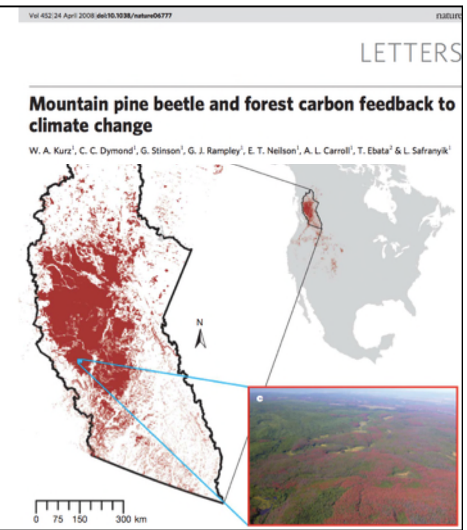
Disturbance, Recovery, and NEP

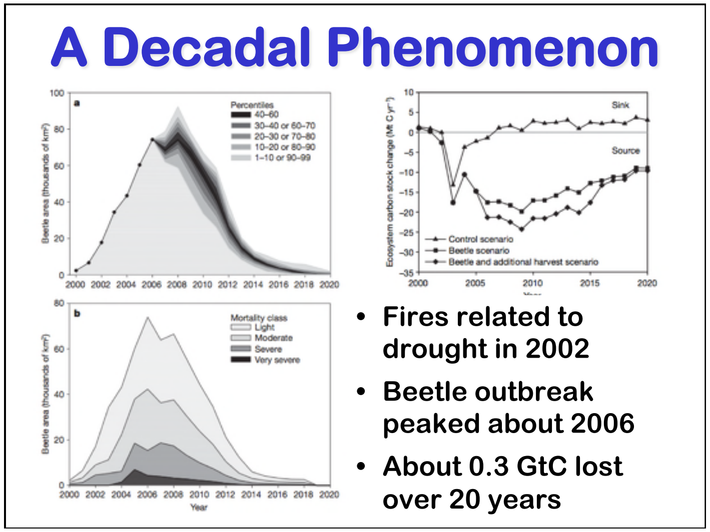


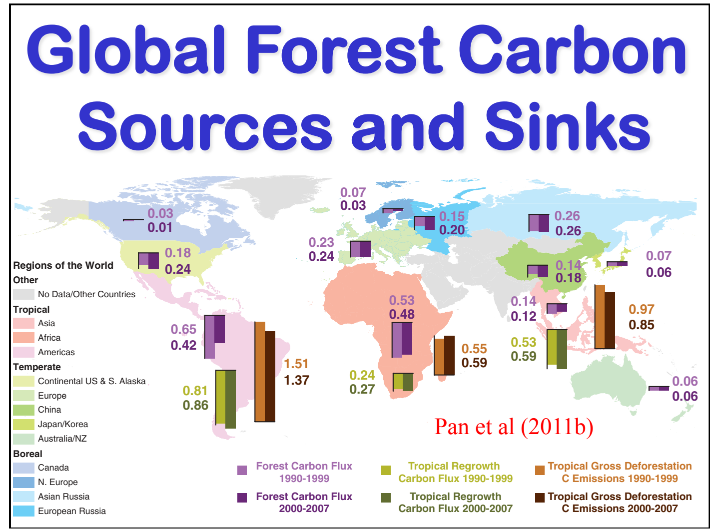
Pan et al (2011a)

Decades of carbon loss following disturbance, decades of slow carbon gain, eventual equilibration

Bugs!




A Decadal Phenomenon
Percentiles
40–60
30–40 or 60–70
20–30 or 70–80
10–20 or 80–90
1–10 or 90–99
Beetle area (thousands of km²)
Mortality class
Light
Moderate
Severe
Very severe
Year
Sink
Source
Ecosystem carbon stock change (Mt C yr⁻¹)
Control scenario
Beetle scenario
Beetle and additional harvest scenario
• Fires related to drought in 2002
• Beetle outbreak peaked about 2006
• About 0.3 GtC lost over 20 years


Global Forest Carbon Sources and Sinks
Regions of the World
Other
No Data/Other Countries
Tropical
Asia
Africa
Americas
Temperate
Continental US & S. Alaska
Europe
China
Japan/Korea
Australia/NZ
Boreal
Canada
N. Europe
Asian Russia
European Russia
0.03
0.01
0.07
0.03
0.15
0.20
0.26
0.26
0.23
0.24
0.18
0.24
0.14
0.18
0.07
0.06
0.53
0.48
0.14
0.12
0.97
0.85
0.65
0.42
0.55
0.59
0.53
0.59
1.51
1.37
0.24
0.27
0.81
0.86
0.06
0.06
Pan et al (2011b)
Forest Carbon Flux 1990-1999
Forest Carbon Flux 2000-2007
Tropical Regrowth Carbon Flux 1990-1999
Tropical Regrowth Carbon Flux 2000-2007
Tropical Gross Deforestation C Emissions 1990-1999
Tropical Gross Deforestation C Emissions 2000-2007