Dynamic Disequilibrium: A Unified Framework for Carbon research

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Dynamic disequilibrium of the terrestrial carbon cycle under global change

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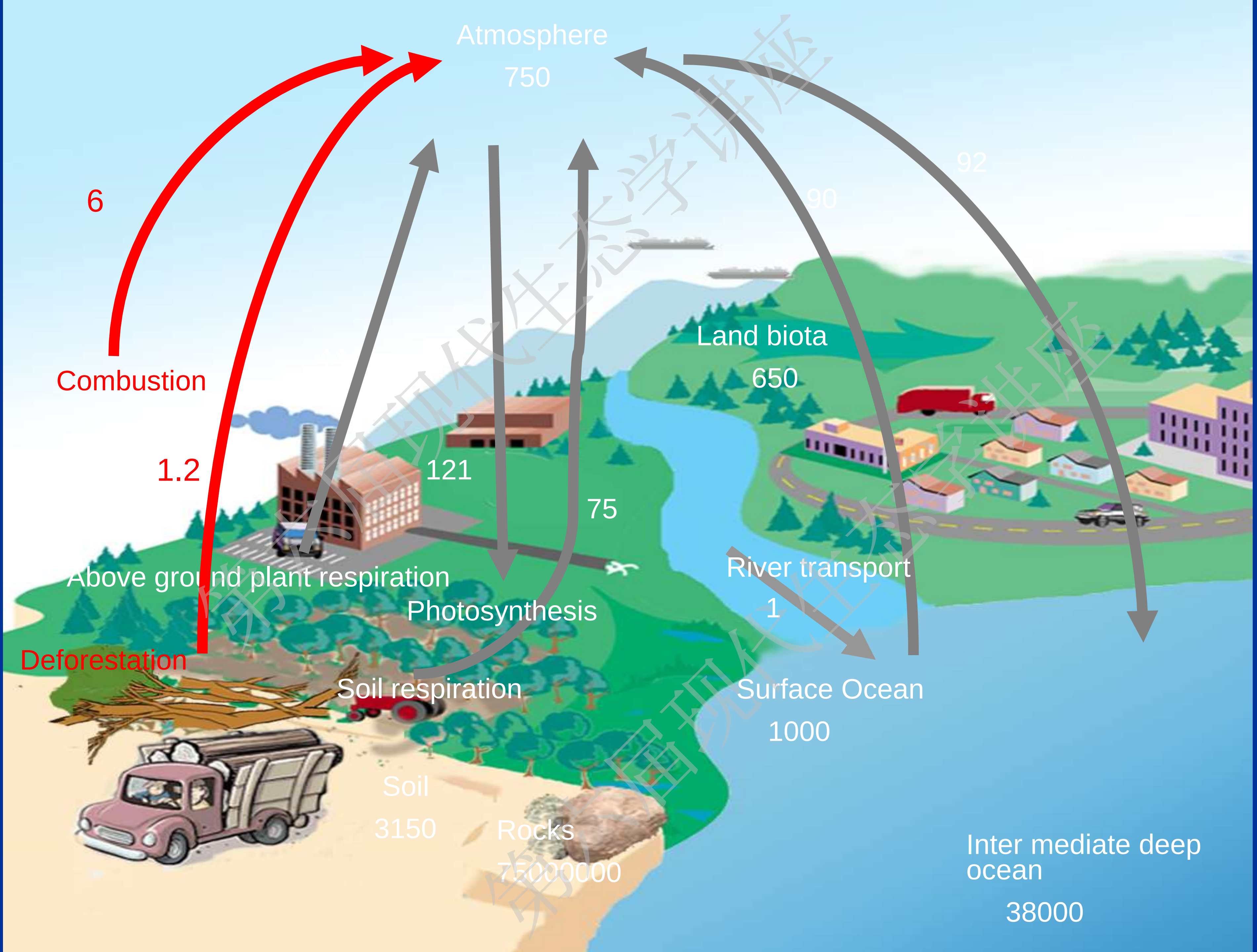
Time-varying magnitude of disequilibrium in carbon cycle.

The disequilibrium is created by disturbances and global change,

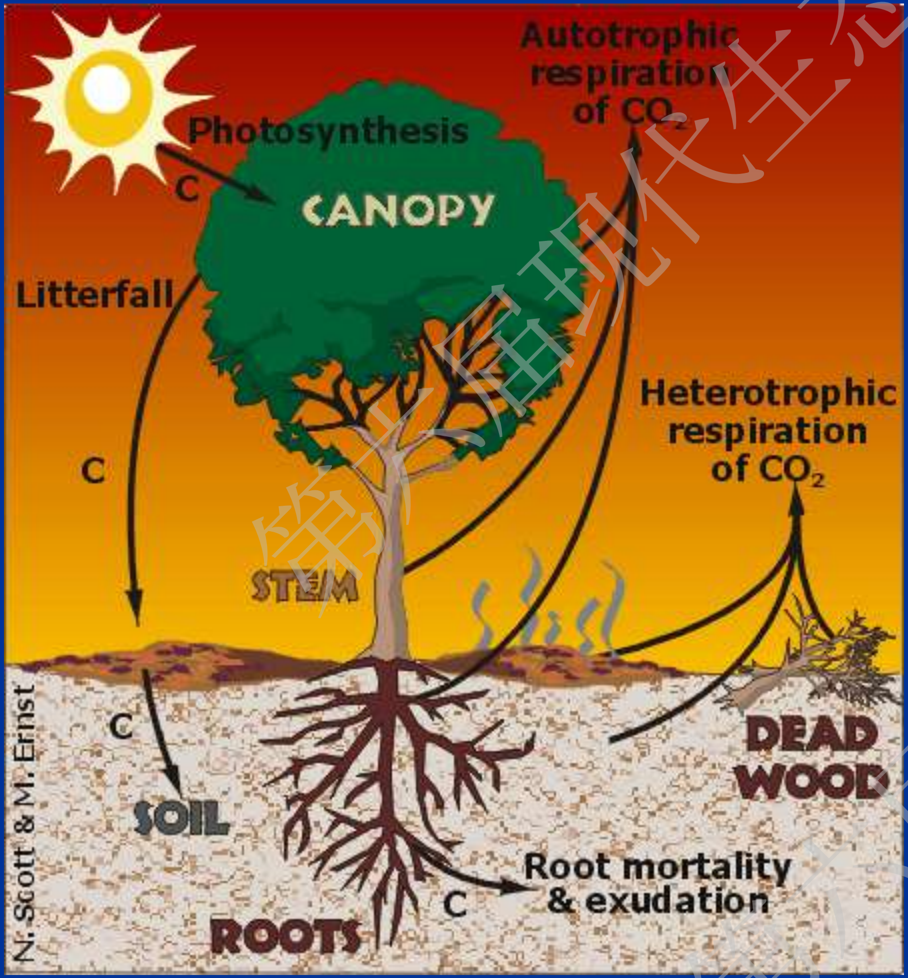
Its varying magnitude with time is driven by internal C processes.



Atmosphere
750
6
Combustion
1.2
Deforestation
121
75
Above ground plant respiration
Photosynthesis
Soil respiration
Land biota
650
90
92
River transport
1
Surface Ocean
1000
Soil
3150
Rocks
75000000
Inter mediate deep ocean
38000

An ultimate goal of carbon research is to quantify

Carbon-climate feedback



The feedback happens when C influx > efflux (i.e. sequestration) or when C influx < efflux (i.e. loss)

That is, carbon cycle is at disequilibrium

Disequilibrium occurs

1. Diel and seasonal cycles
2. Global change
3. Disturbance events
4. Disturbance regime shifts
5. Ecosystem state changes

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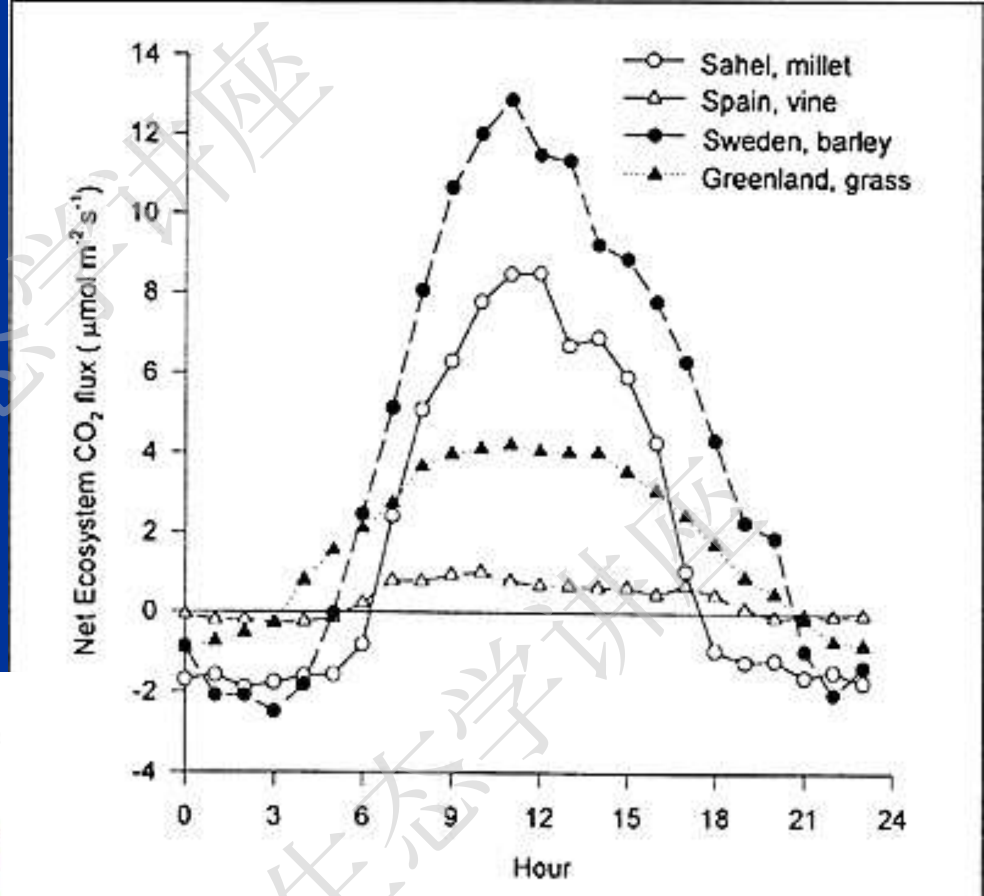
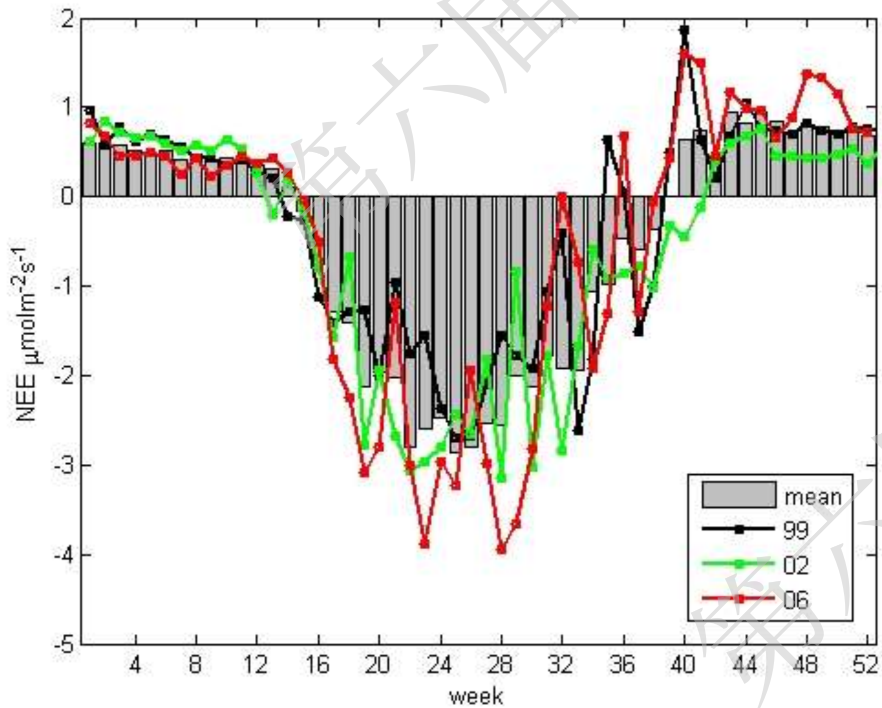
Case I

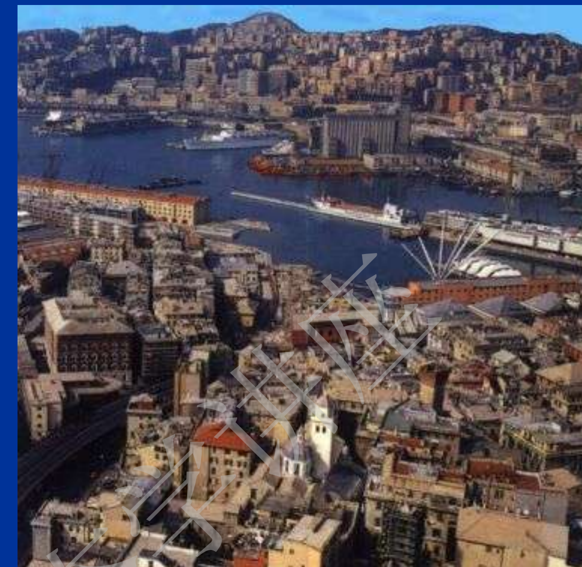
Disequilibrium of carbon influx and efflux occurs in most points of time over a day or a year





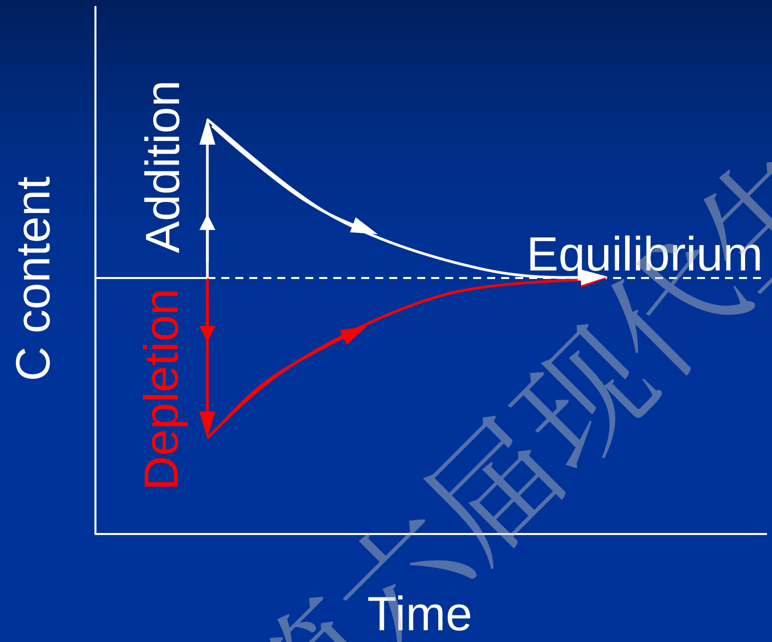
Equilibrium of carbon cycle occurs for yearly averages of influx and efflux

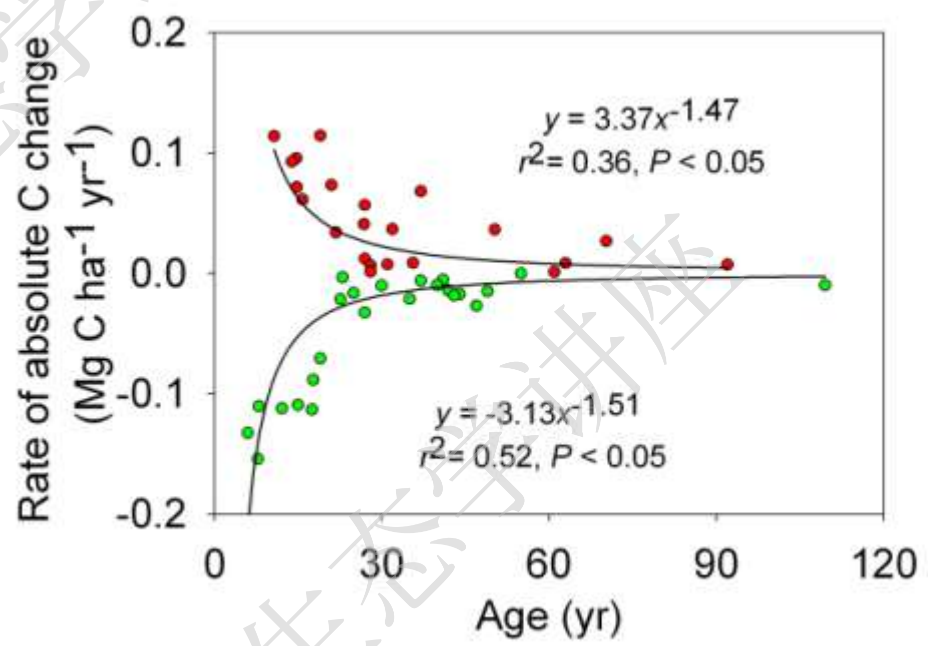
Case II: disturbances



Disturbances alter carbon pools, affect carbon influx and residence times

When disturbances alter pool sizes





Yang et al. 2011
New Phytologist

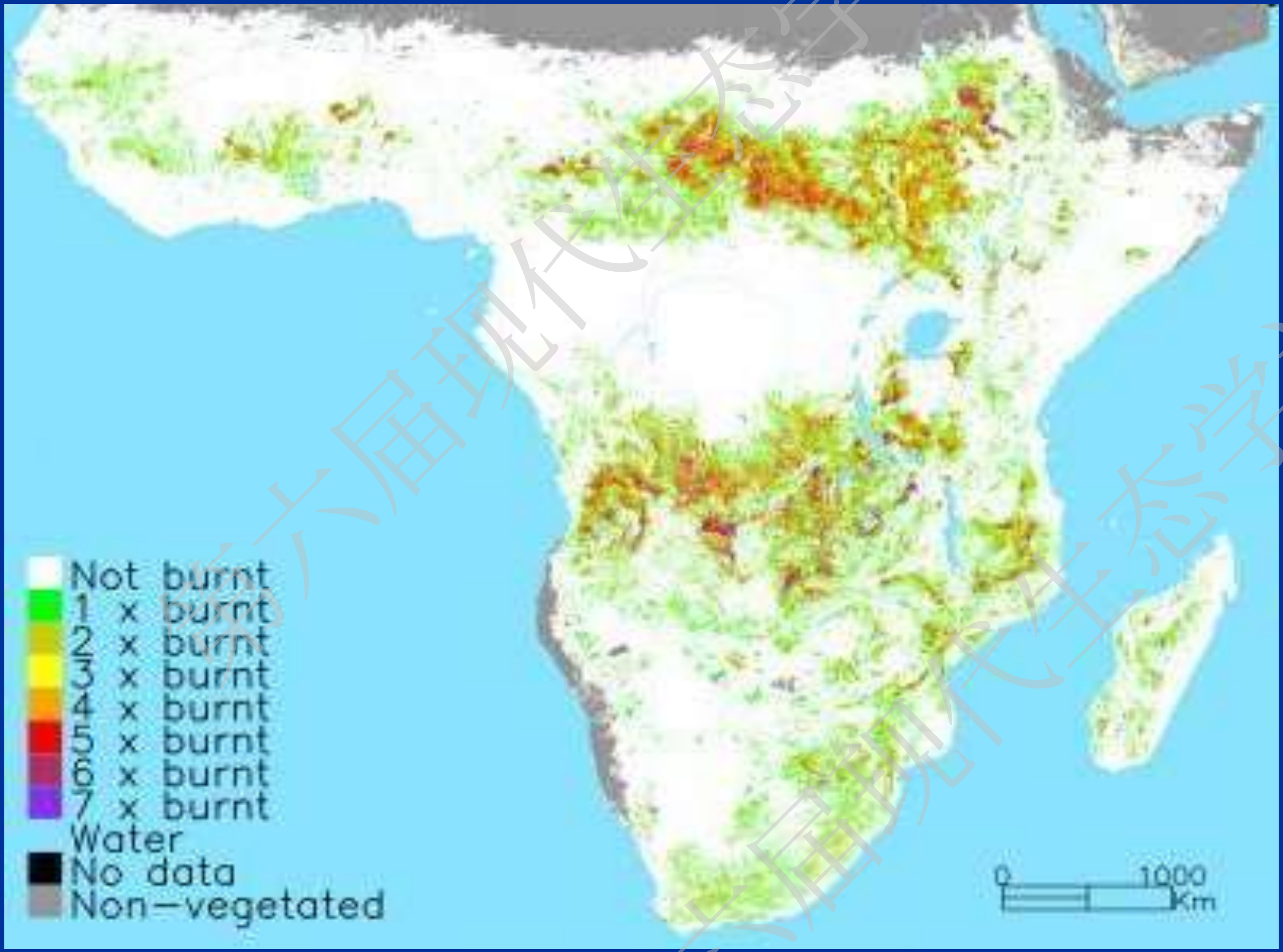
Disequilibrium of carbon cycle occurs in any point of time after disturbance until the ecosystem fully recovers.

Equilibrium of carbon cycle occurs after the ecosystem fully recovered

Samples of disturbance effects on C storage

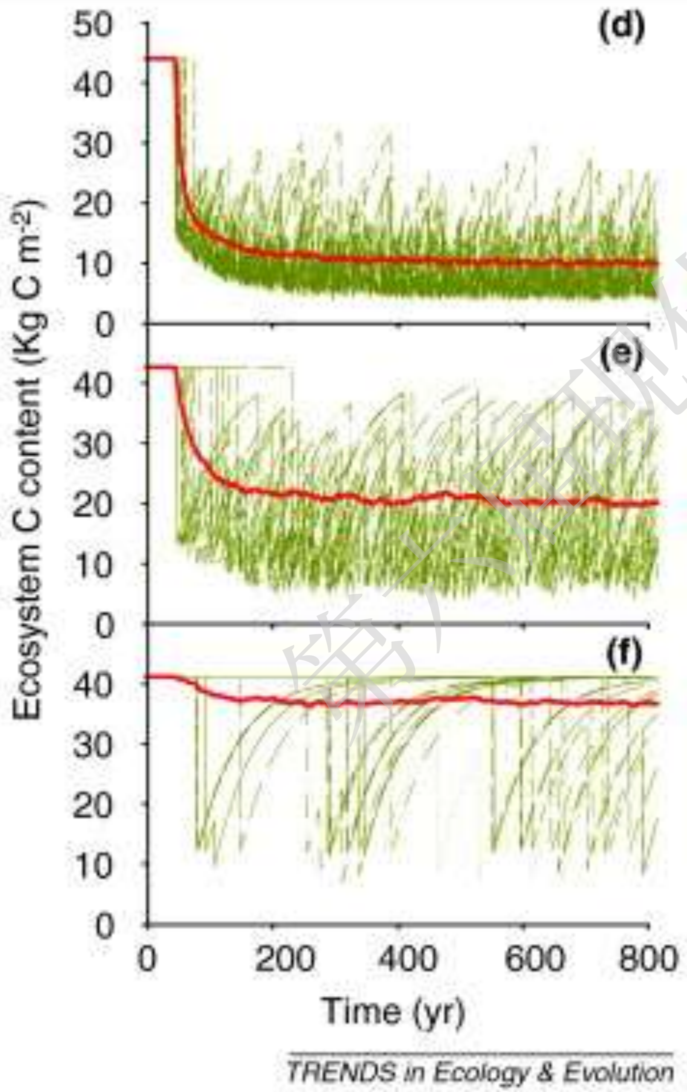
Disturbance	Effect	Spatial Scale	Reference
Land use	1-2 Gt yr^{-1}	Global	Houghton, 1997, 2003 Strassmann et al. 2008
Fire	1.3 -3.5 Gt yr^{-1}	Global	Hoelzemann et al. (2004) van der Werf et al. (2004)
Drought	0.5 Gt	Europe	Heathwaite (1993)
Insect outbreak	0.135 Gt	Canada	Kurz and Apps (1999)
Storm	0.105 Gt	region	Chambers et al. (2007)

Case III: Disturbance regimes



Each region has its own disturbance regime as characterized by disturbance frequency, severity, and spatial cover

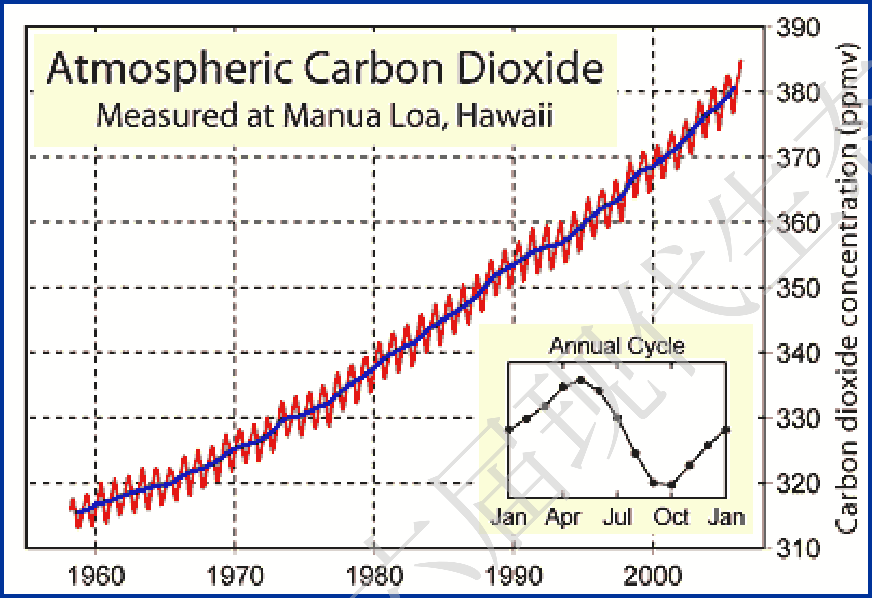
occurrence of fire activity in sub-Saharan Africa for a period 2000-2007

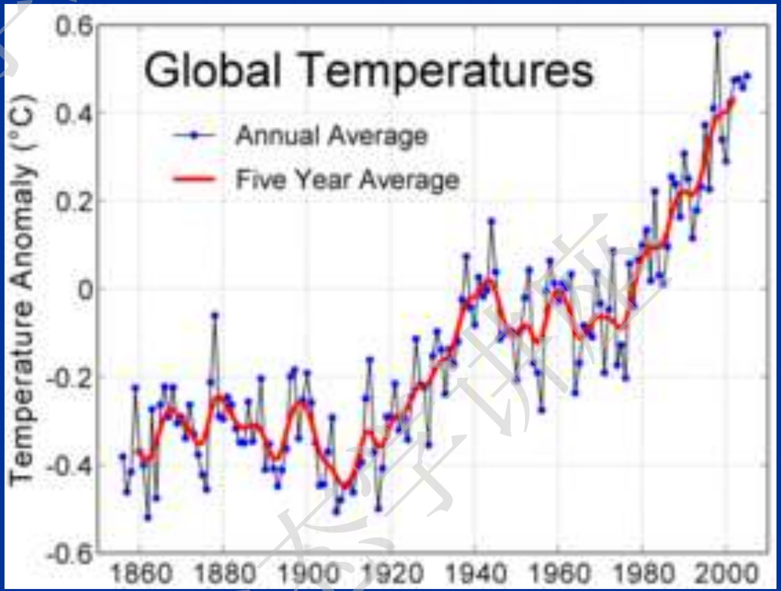


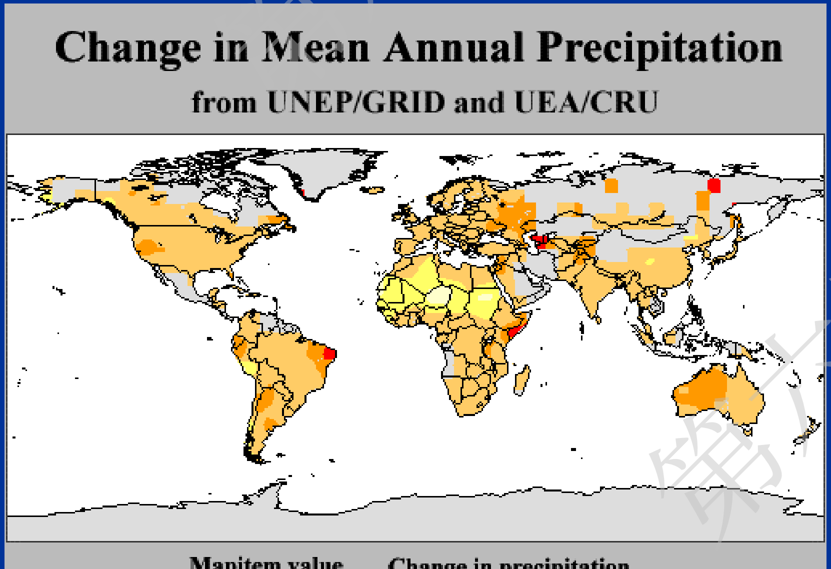
Disequilibrium occurs when the disturbance regime in the region shifts (i.e. is non-stationary)

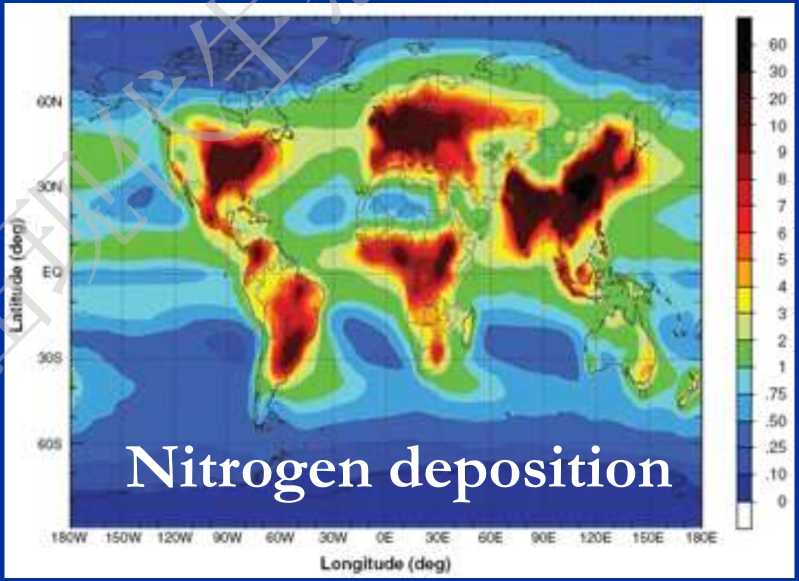
Equilibrium occurs when the disturbance regime in a region does not shift (i.e. is stationary).

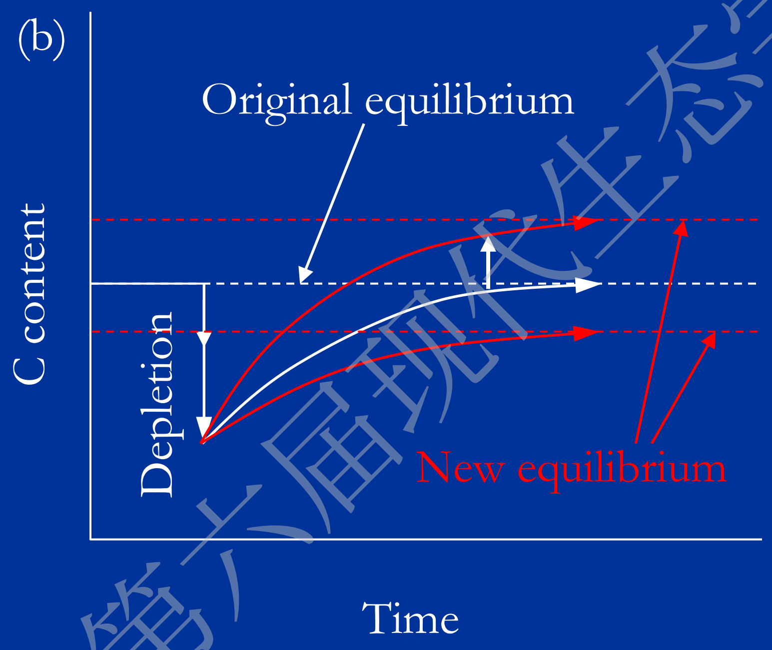
Case IV: Global change











Global change directly influences carbon influx and residence times

Disequilibrium occurs when directional changes in global environment happen

Equilibrium occurs only if there is no directional changes in global environment (e.g. pre-industrial [CO2])

Global change effects on land C sink

Factor	Influx	Residence time	Uncertainty
Rising atmospheric CO_2	↑	↑	Nitrogen regulation
Climate warming	↑	↓	Species composition
Nitrogen deposition	↑	↓	Carbon partitioning
Precipitation	↑↓	↑↓	Variable scenarios

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Case V: Ecosystem state changes

Permafrost soil ←→ active soil layers

Forests ←→ grasslands

Forests ←→ bioenergy crop

Grasslands ←→ woody encroachment

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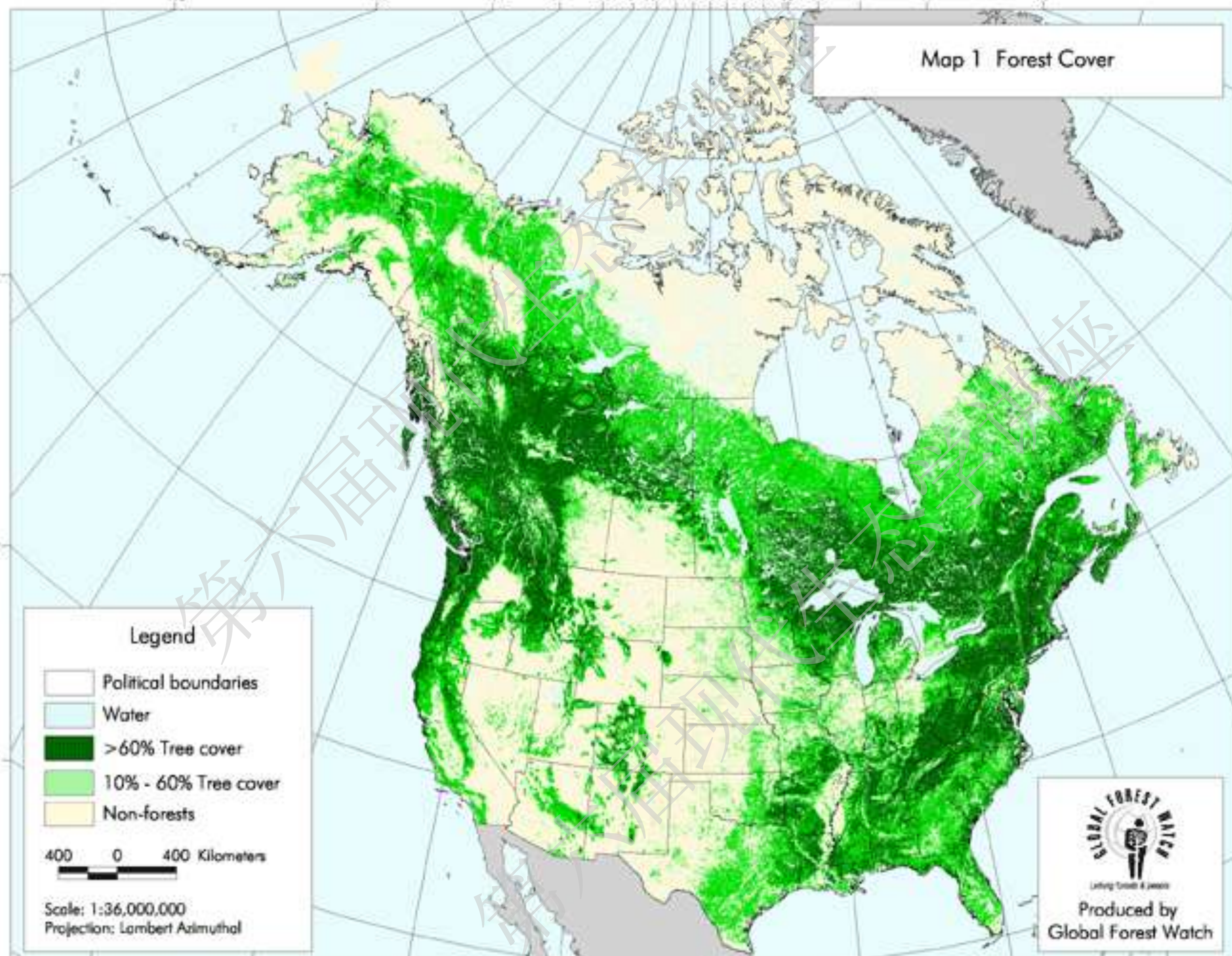
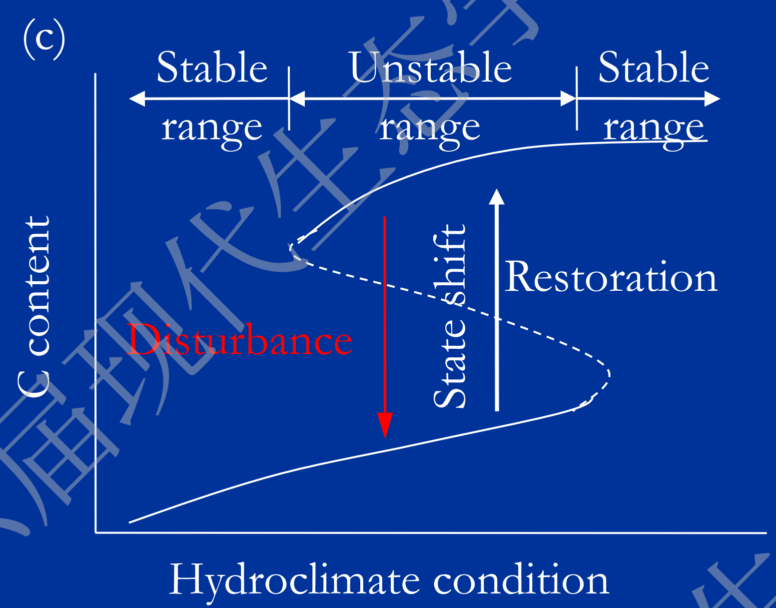
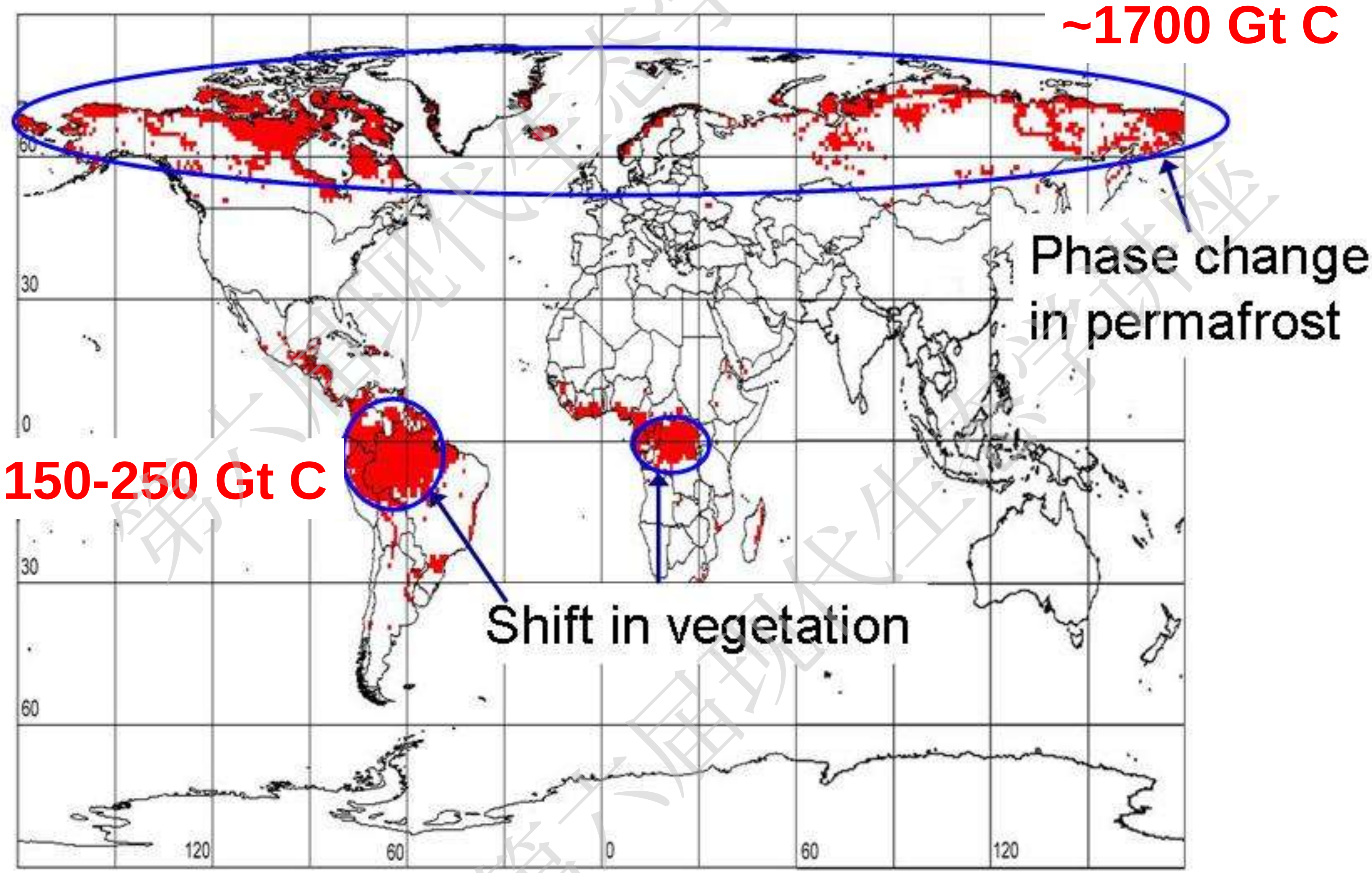

Map 1 Forest Cover
Legend
Political boundaries
Water
>60% Tree cover
10% - 60% Tree cover
Non-forests
400 0 400 Kilometers
Scale: 1:36,000,000
Projection: Lambert Azimuthal
GLOBAL FOREST WATCH
Produced by
Global Forest Watch



Disequilibrium occurs as an ecosystem changes from the original to alternative states

C cycle can be at equilibrium at either the original or alternative states

Regions vulnerable to state changes

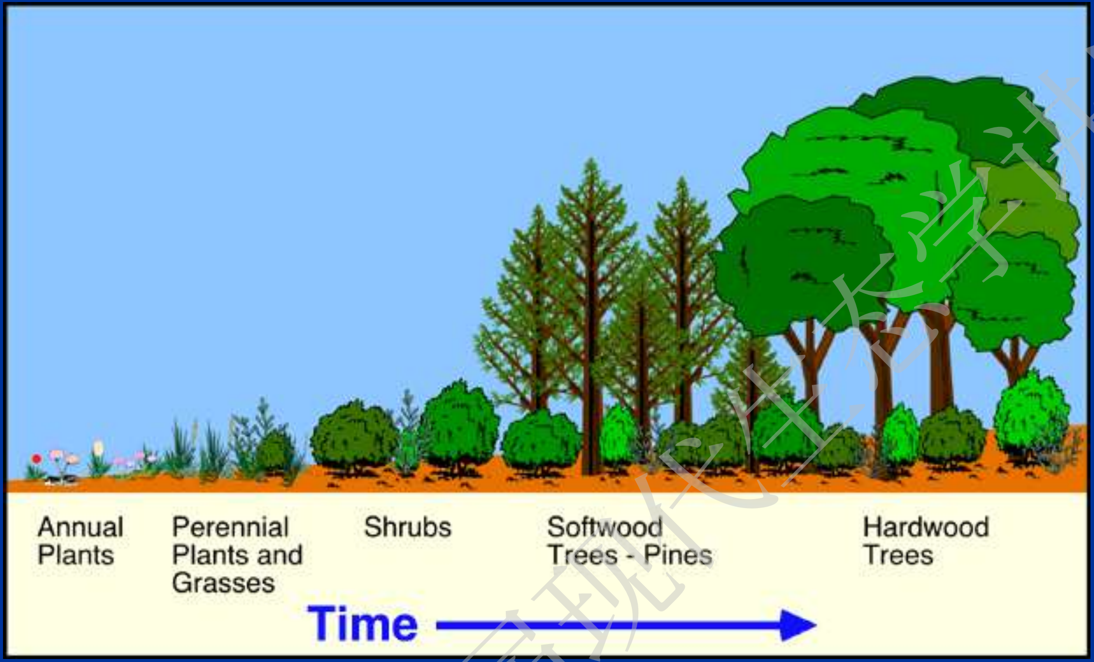


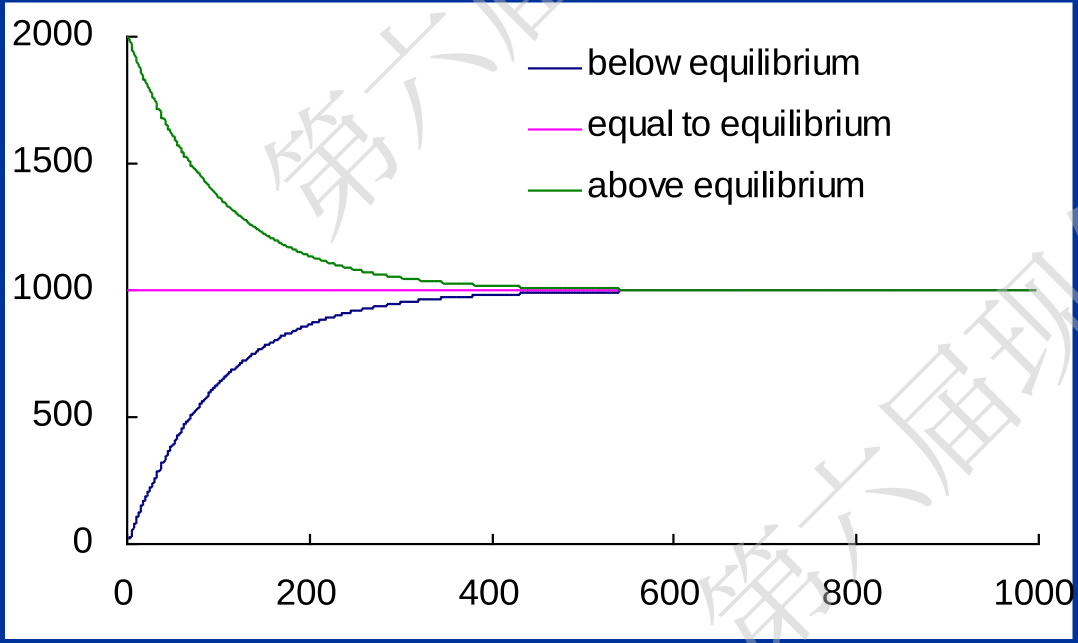
Five Cases of equilibrium and disequilibrium

Case	Disequilibrium	Equilibrium
Diel and seasonal cycles	Imbalances of C influx and efflux are driven by cyclic environmental change.	Annual averages of C influx and efflux
Global change	Direct effects on influx and/or residence time; Indirect effects on ecosystem structure and disturbance regimes	At a reference condition (e.g. pre-industrial [CO_2]) and a new equilibrium at the given set of changed conditions
Disturbance event	Increase or decrease in (1) C pools; (2) C influx; and (3) carbon residence times	When the ecosystem fully recovers after a disturbance.
Disturbance regimes	Changes in disturbance frequency and severity, and spatial covers	When the disturbance regime does not shift (i.e. is stationary).
Ecosystem state change	Carbon accumulates or loses as an ecosystem changes from the original to alternative states	At the original and alternative states

Among the five cases, external forces cause disequilibrium.

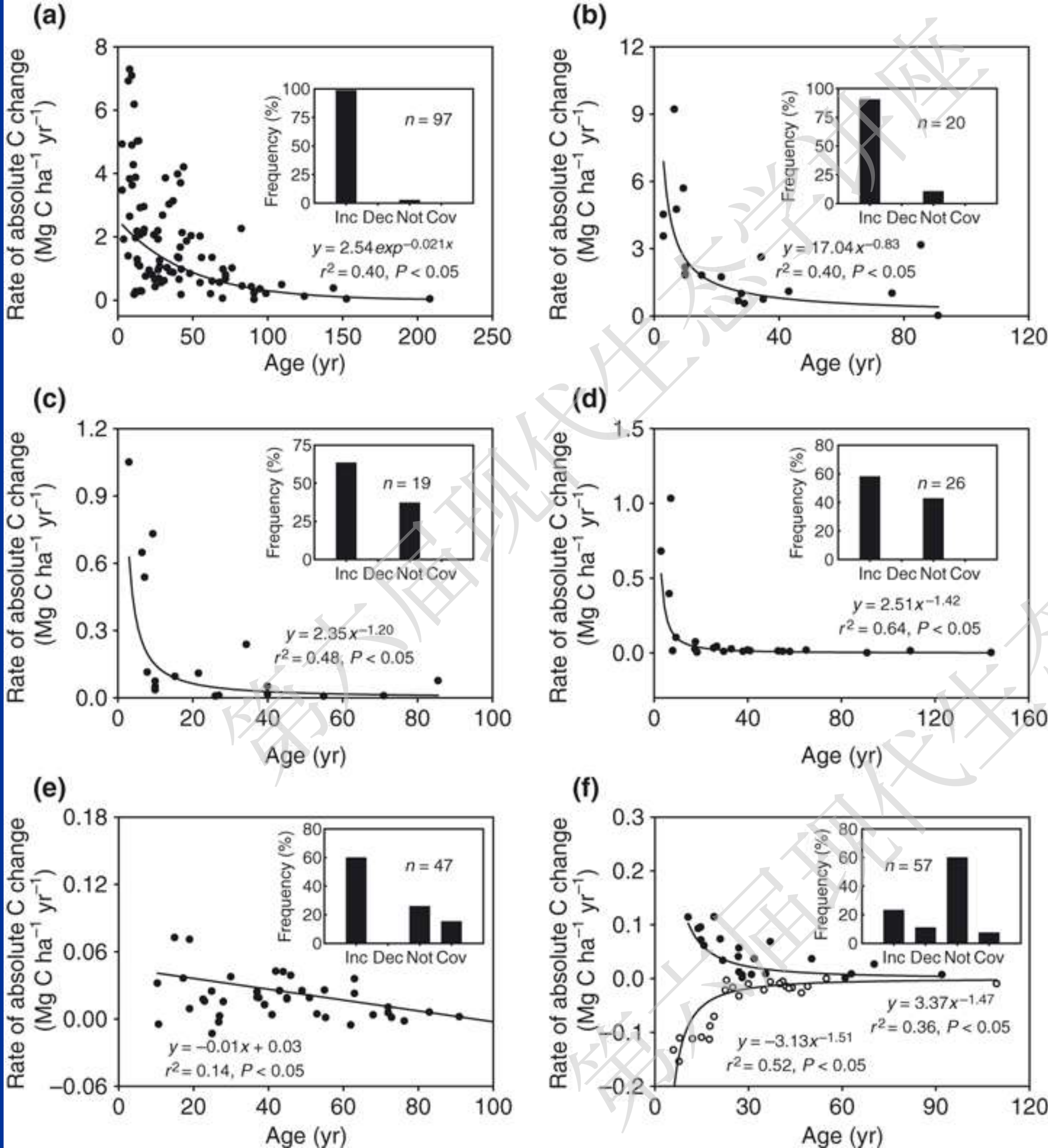
What determine the equilibrium?





1. Internal C processes to equilibrate efflux with influx as in an example of forest succession

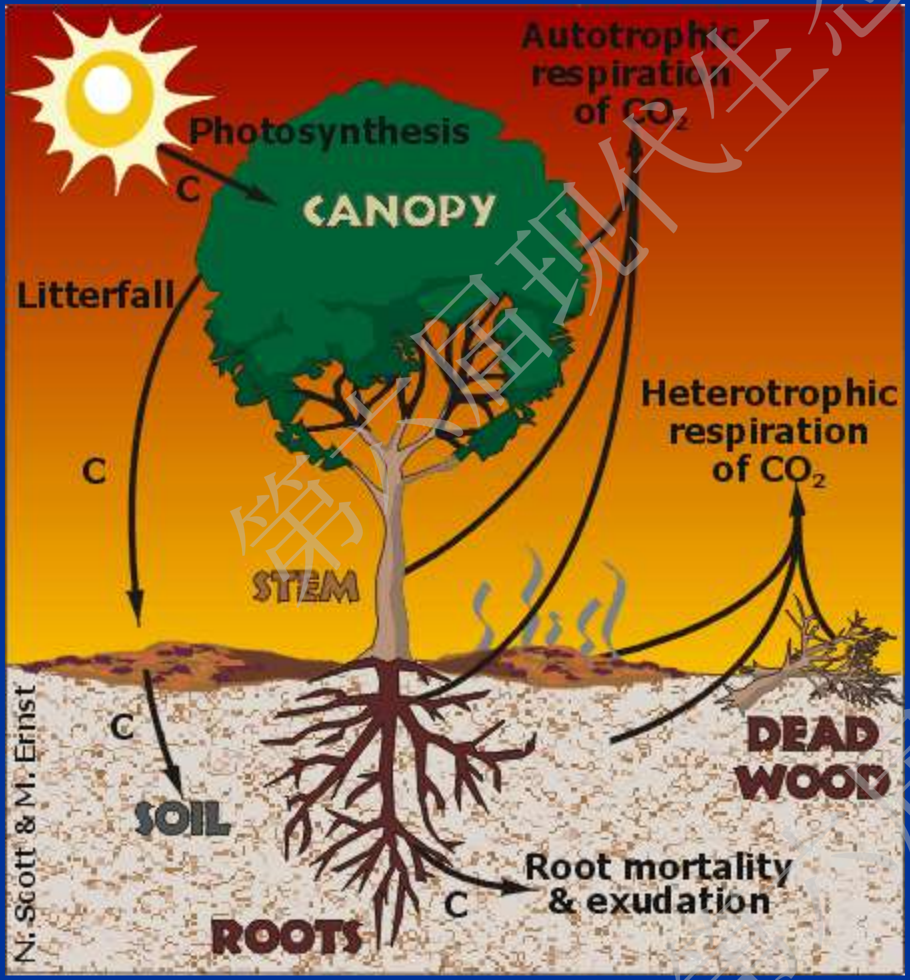
2. C sink strength becomes smaller as efflux is equalized with influx



When an ecosystem has enough time to recover, the rate of change in carbon pools approaches zero.

Yang et al. 2011, New Phytologist

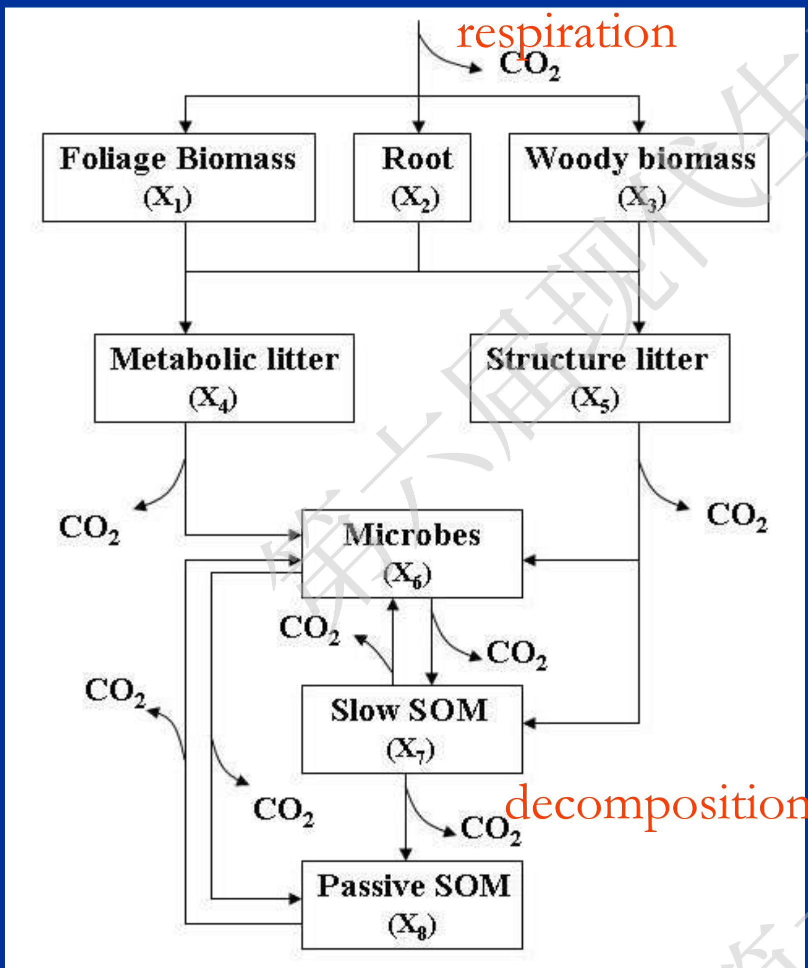
Properties of internal C processes



1. Photosynthesis as the primary C influx pathway
2. Compartmentalization,
3. partitioning among pools
4. donor-pool dominated carbon transfers
5. 1st-order linear transfers from the donor pools

Model representation of ecosystem carbon processes

photosynthesis



Mostly by pool-flux models

$$\frac{dX(t)}{dt} = x(t)AX(t) + bU(t)$$

$$X(0) = X_0$$

Governing equations

$$\frac{dX(t)}{dt} = \xi(t)AX(t) + bU(t)$$

$$X(0) = X_0$$

<u>Structure</u>:

1. Robust flow pathways shared among models;
2. Uncertain response functions to forcing variables (ξ).

<u>Parameters</u>:

1. C influx: $P(t)$;
2. Residence time: $t_E = f(A,b)$
3. Initial values: X_0

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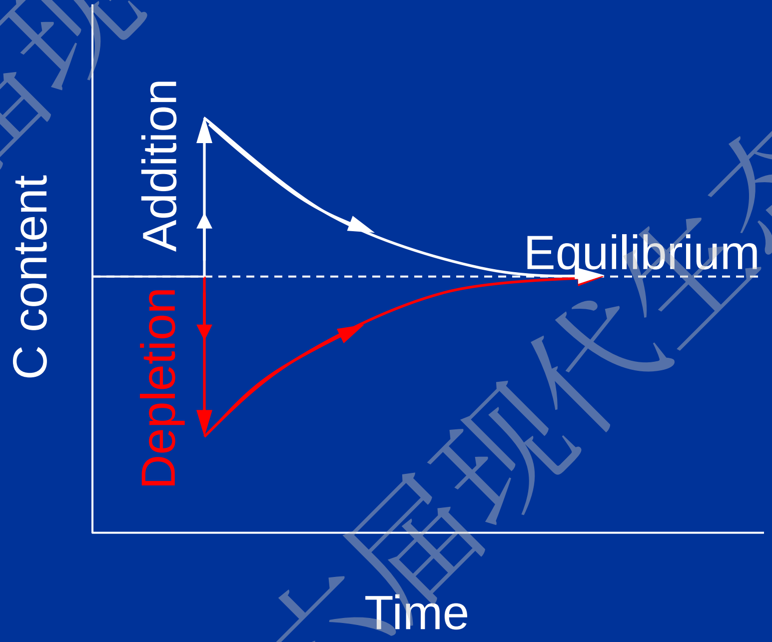
Disequilibrium and its varying magnitude



Dynamic Disequilibrium (DD)

- Carbon-climate feedback occurs only when terrestrial carbon cycle is at disequilibrium.
- Ecosystems have internal processes that drive carbon cycle toward equilibrium (i.e. recovery force).
- External forces, such as disturbances and global change, create disequlibrium by altering internal C processes and pool sizes.
- The two forces are opposite and act against each other to determine future C sink dynamics

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Definition

The dynamic disequilibrium concept refers to a time-varying magnitude of the carbon-cycle disequilibrium.

The disequilibrium is created by disturbances and global change

Its varying magnitude with time is driven by internal carbon processes.

Predictions by the dynamic disequilibrium framework

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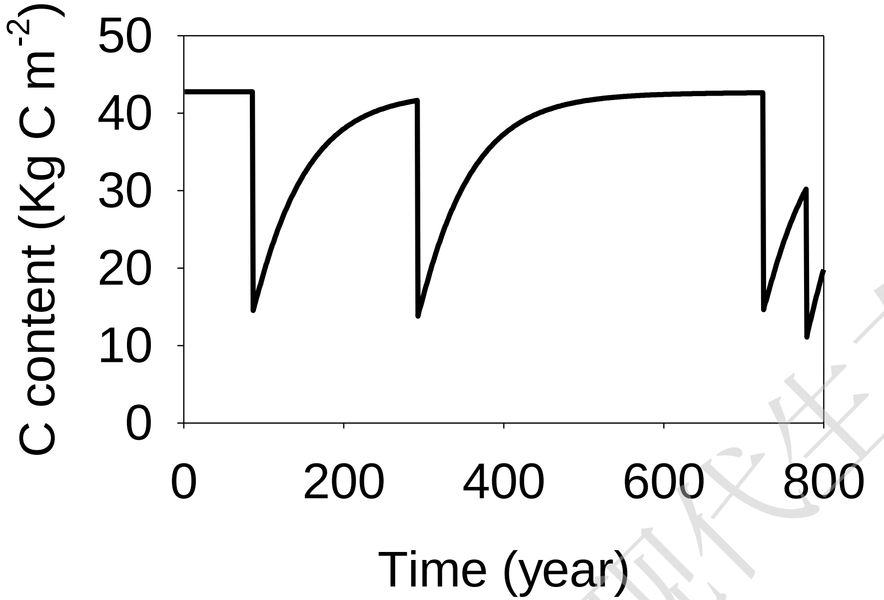
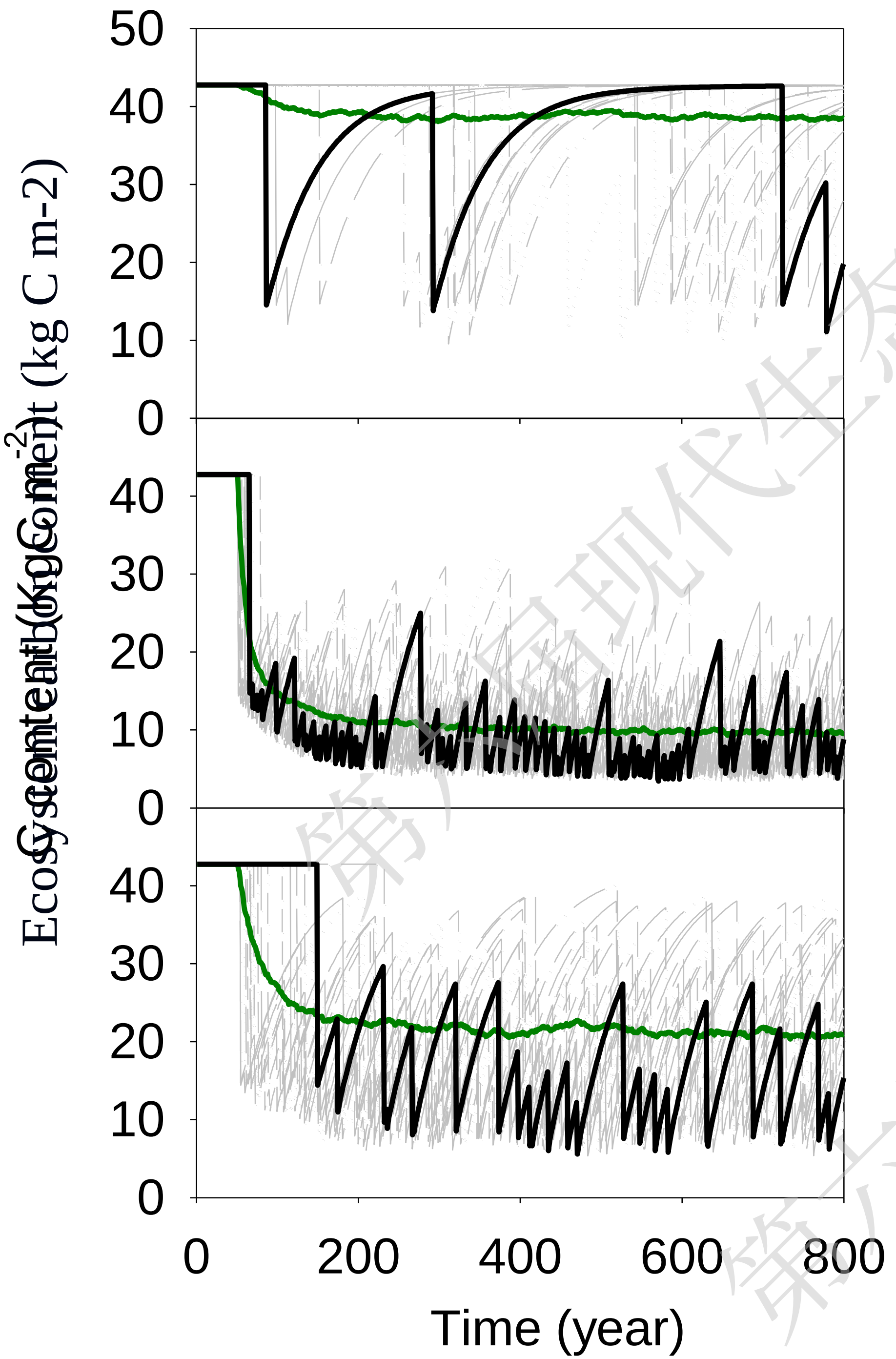


Prediction 1: Disturbance causes temporal changes in C sink and source within one disturbance-recovery episode but has no impact on long-term and regional C sink dynamics unless its regime changes.



Prediction 1: Disturbance causes temporal changes in C sink and source within one disturbance-recovery episode but has no impact on long-term and regional C sink dynamics unless its regime changes

Prediction 2: The realizable C storage is smaller than the equilibrium level when disturbances occur frequently

Prediction 3: More positive feedback occurs from land ecosystems to climate change if climate change causes more frequent, severe, and extensive disturbances

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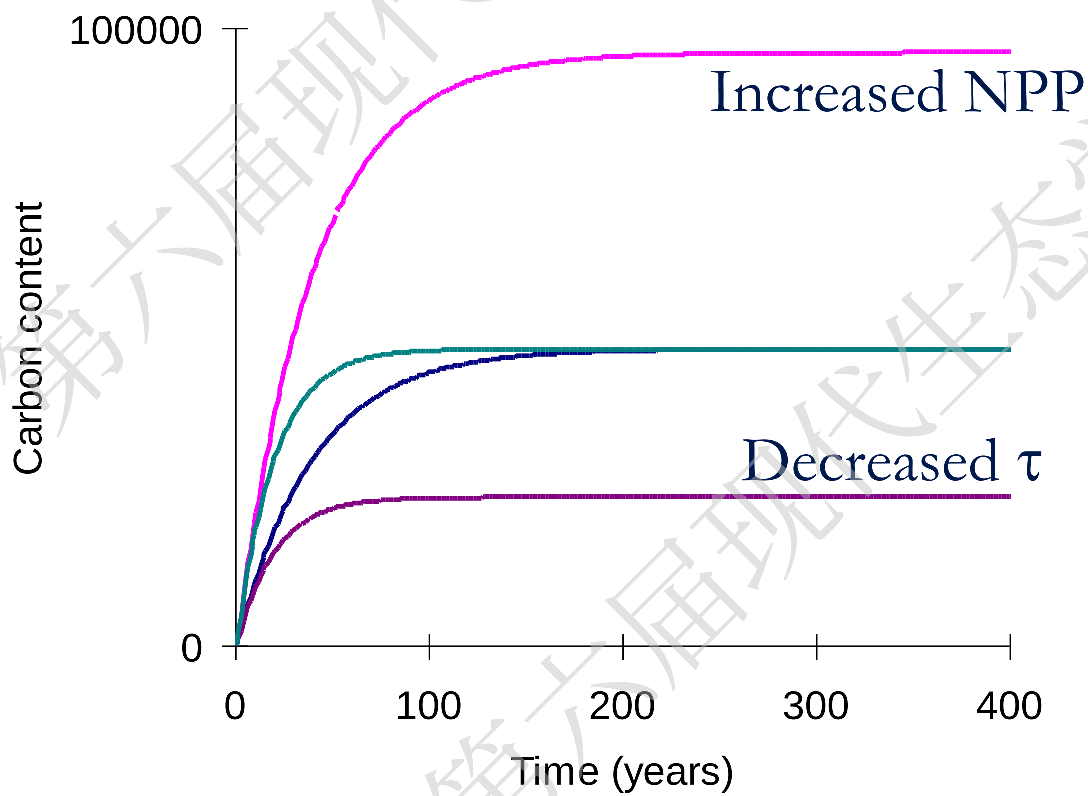
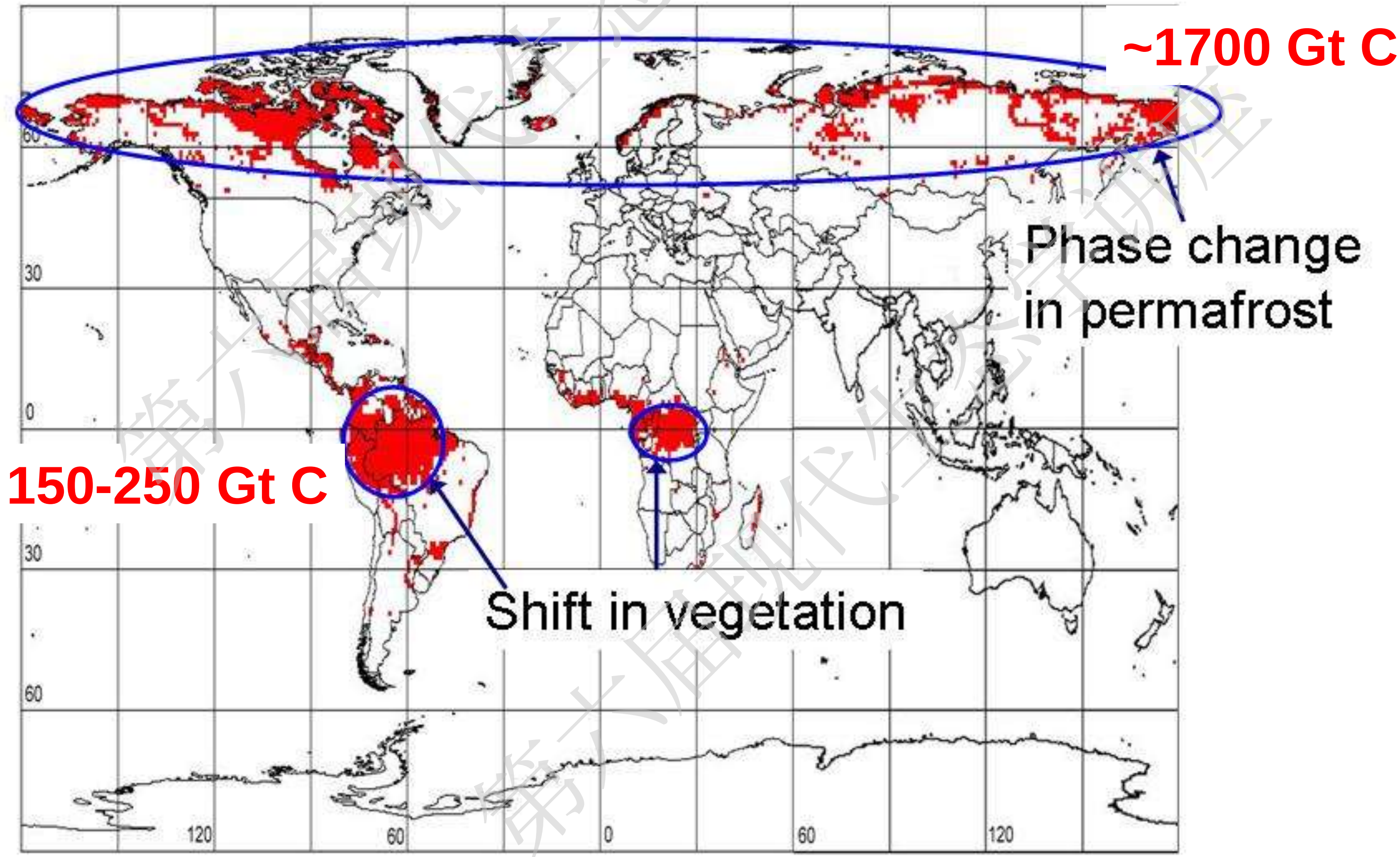
Prediction 4: Ecosystem C storage capacity decreases if global change and disturbance reduce canopy photosynthetic C influx and residence times, and vice versa.



Prediction 5: Global C cycle becomes destabilized if global change and disturbances trigger state changes in regions where vast C reserves are at risk.



Quantifying the disequilibrium and its varying magnitude

Case	**Key parameter**
Diel and seasonal change	Photosynthesis and respiration varying with diel and seasonal cycles of environment
Global change	Environmental scalars to simulate direct effects of global change
Single disturbance event	Three sets of parameters related to C influx, residence time, and initial pool size
Disturbance regime shift	Joint probability distributions of disturbance frequency and severity over space and time
Ecosystem state change	Changes in structure and parameters of C models to characterize changed ecosystem structures

Among the four cases, studies have been done to understand impacts of global change and disturbance events on C cycle whereas disturbance regime shifts and ecosystem state changes have more profound impacts on C cycle but not been studied much

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2011 TREE

Conclusions

1. DD framework to integrate C cycles with disturbance ecology
   a. DD exists in nature with directional global change
   b. An angle to analyze the C cycles
2. Internal C processes drive C cycles toward equilibrium
   a. Fully expressed in the governing equation with three sets of parameters
   b. Data assimilation to improve models for forecasting C sink
3. External forces cause disequilibrium

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