Radiocarbon in Terrestrial Systems

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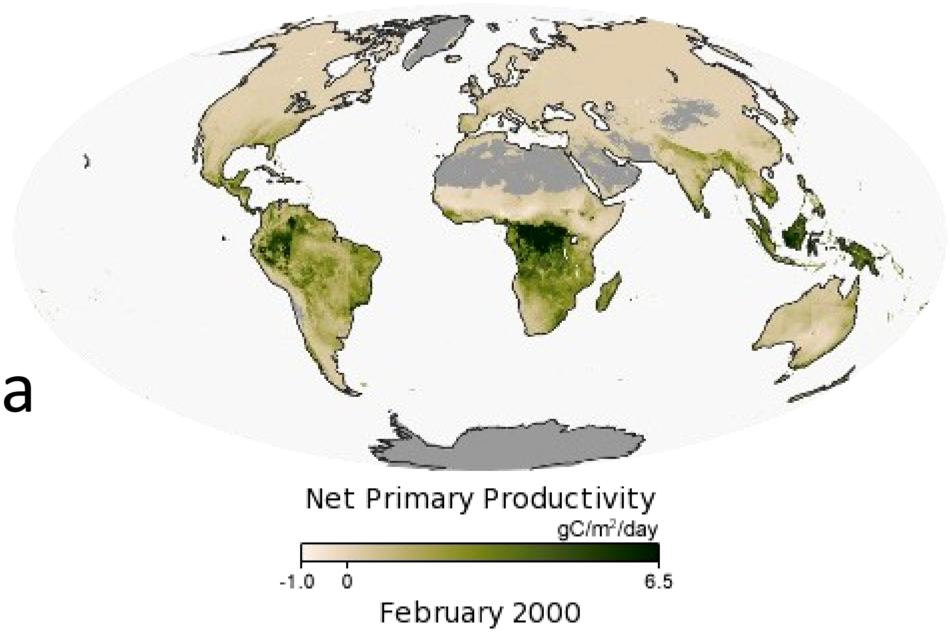
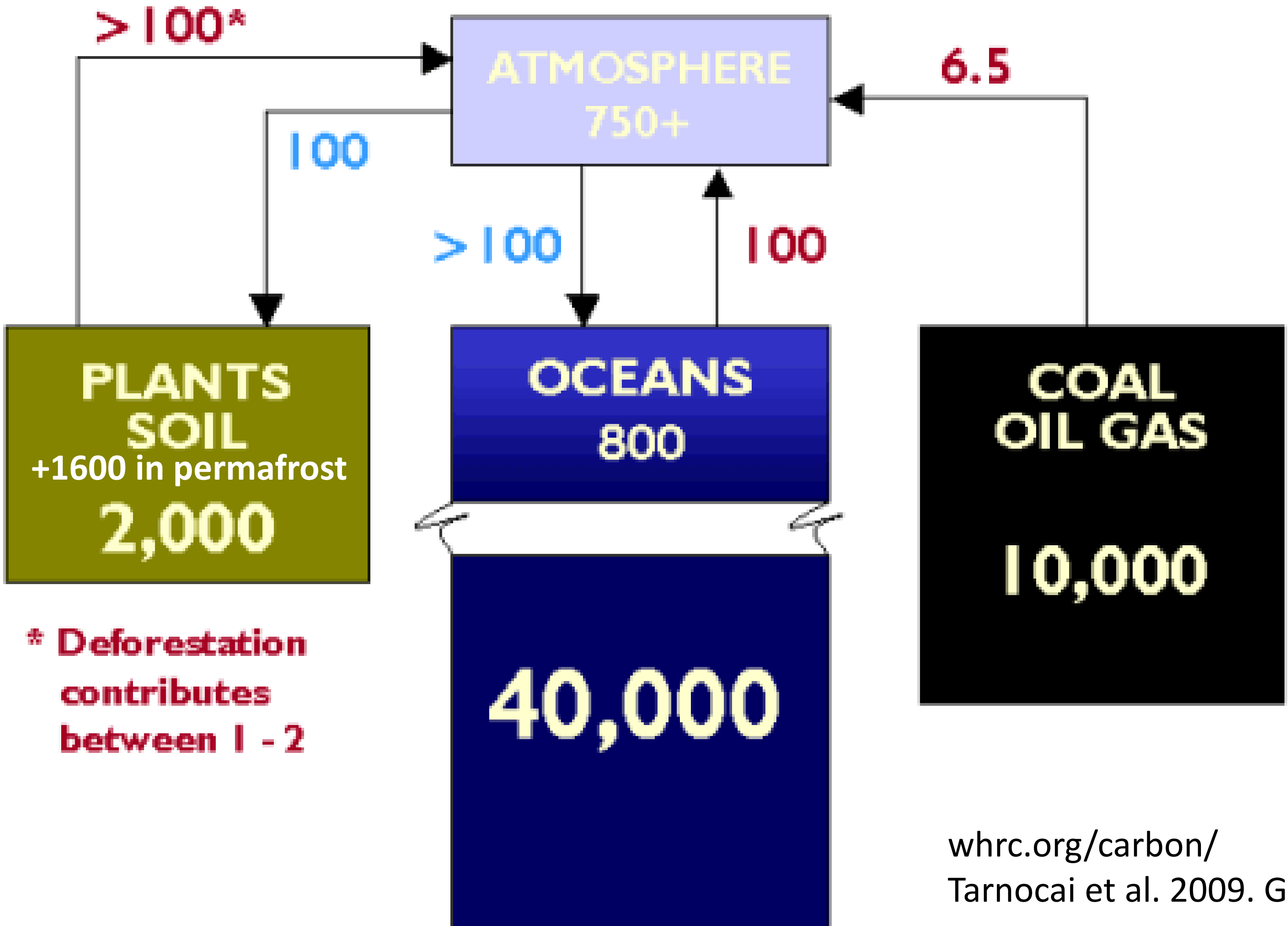


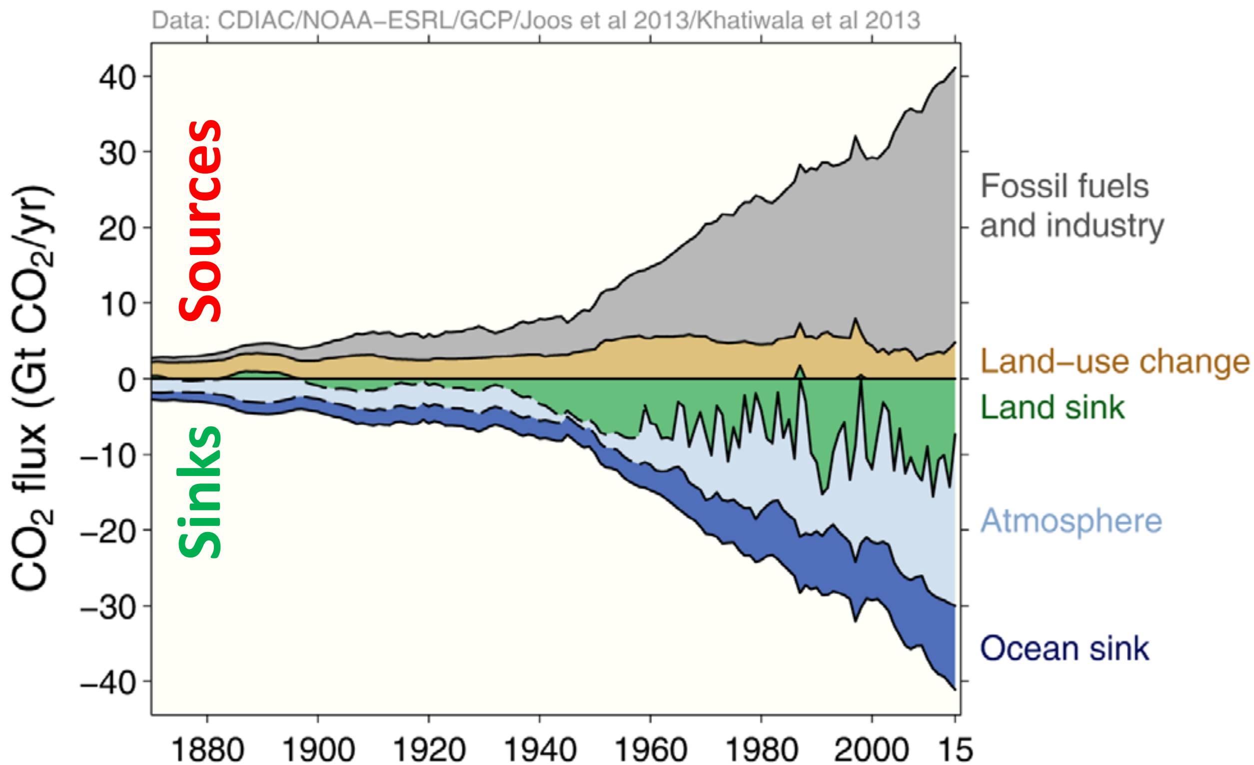
Global Flows of Carbon (Pg C/yr)



whrc.org/carbon/
Tarnocai et al. 2009. GBC

Global carbon budget 2016

Fate of anthropogenic CO_2 emissions (2006-2015)



34.1 $GtCO_2$/yr

91%

9%

3.5 $GtCO_2$/yr

11.6 $GtCO_2$/yr

31%

16.4 $GtCO_2$/yr

44%

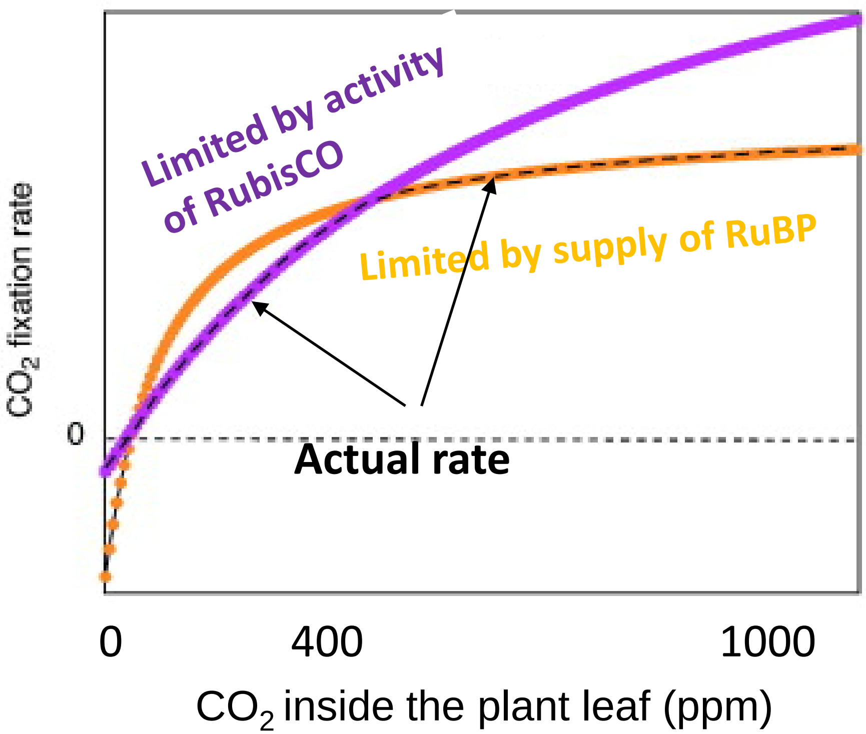
26%

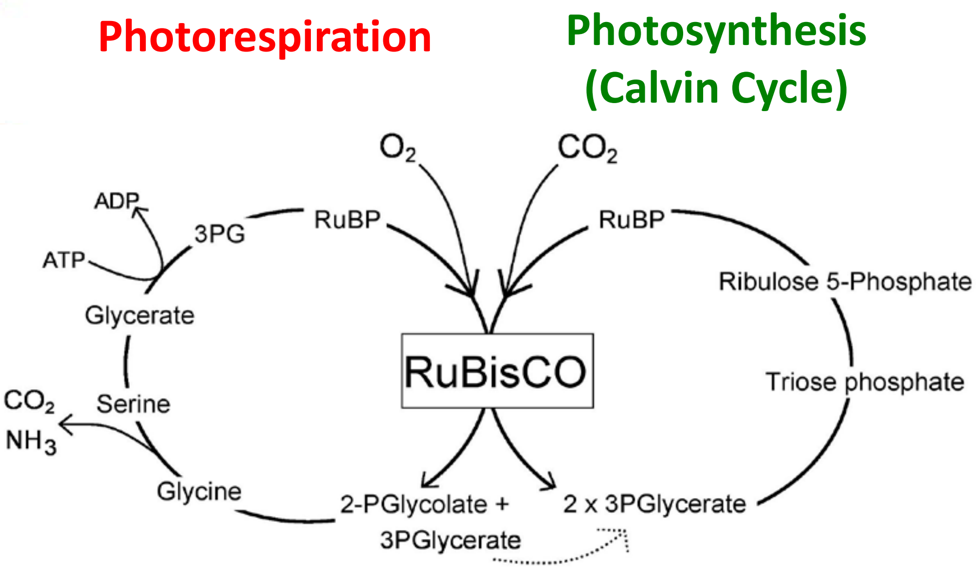
9.7 $GtCO_2$/yr

Why is the land currently a C sink?

Most Plants use the C3 Photosynthetic Pathway

CO_2 competes with O_2 for Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO)

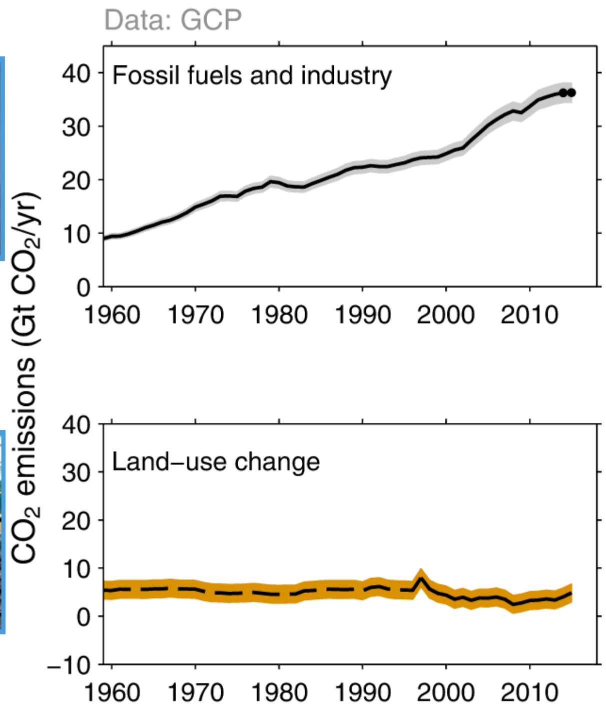


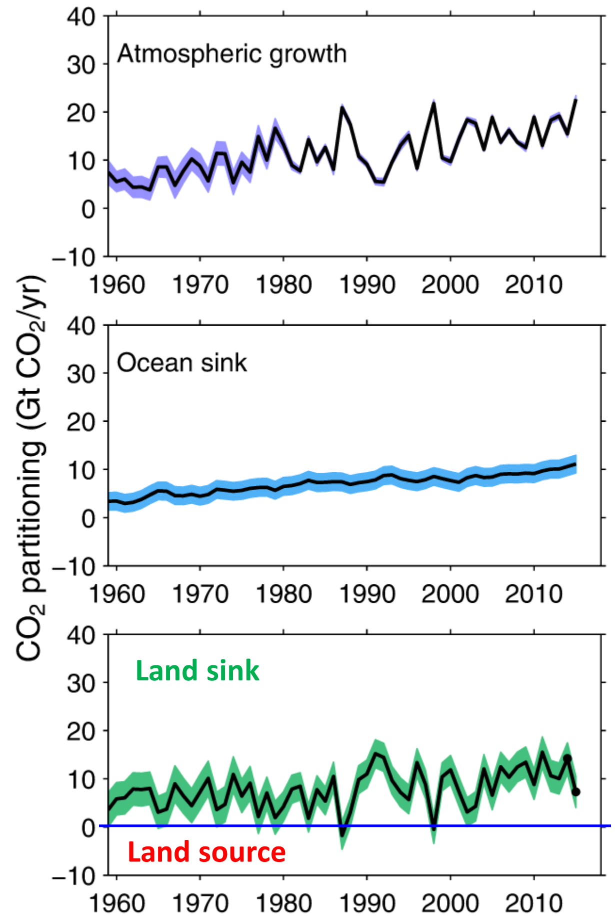


Flood et al. 2011. Trends

Changes in the budget over time

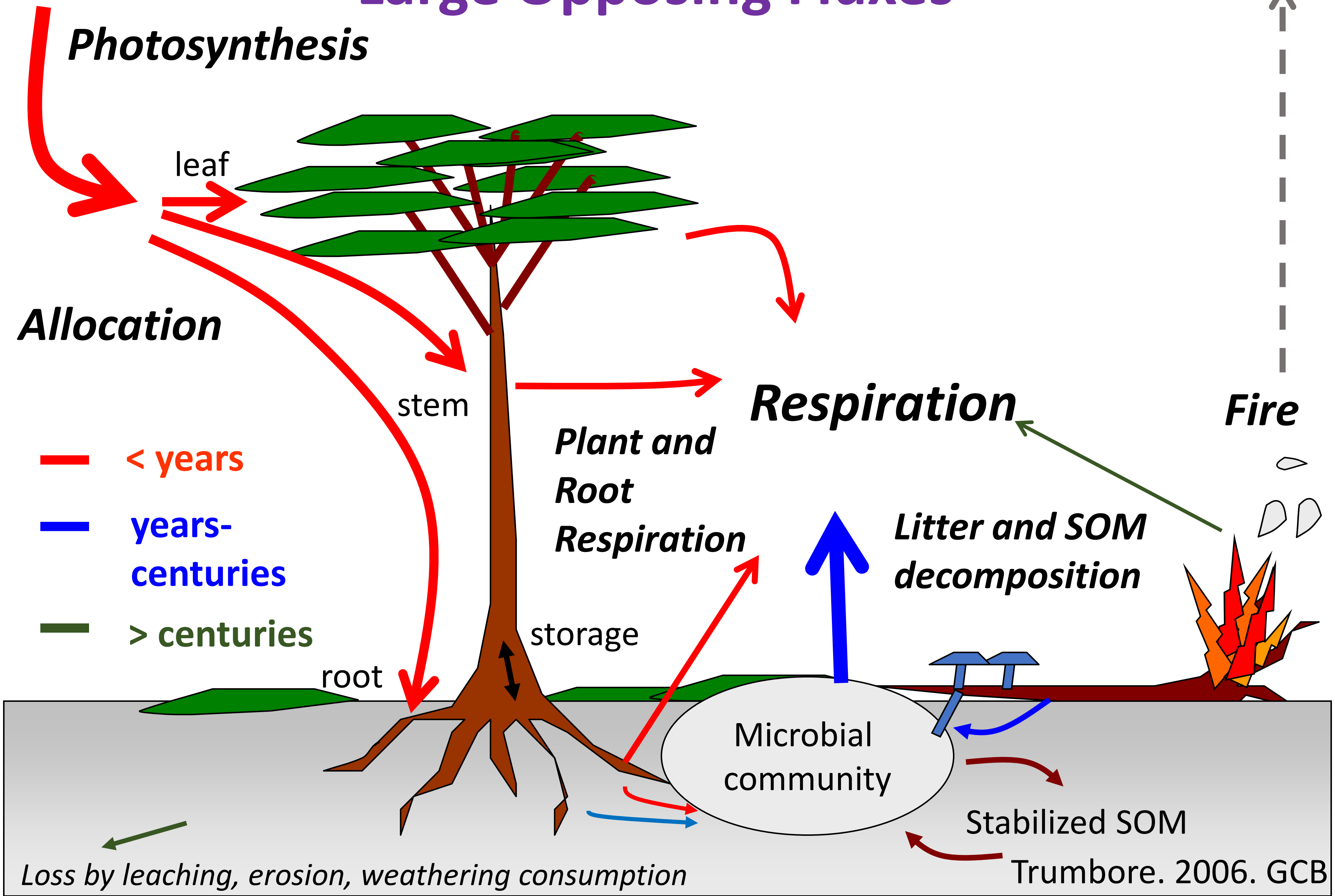
Why is the land-atmosphere flux so variable from year to year?





Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

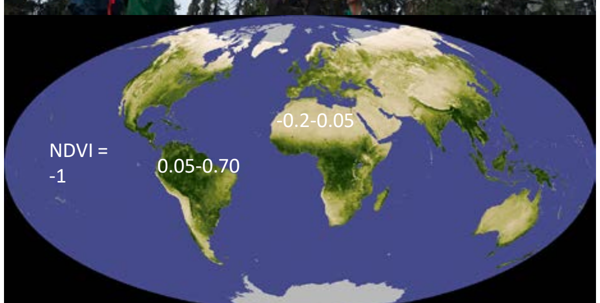
Land-Atmosphere C Exchange: Large Opposing Fluxes



Trumbore. 2006. GCB

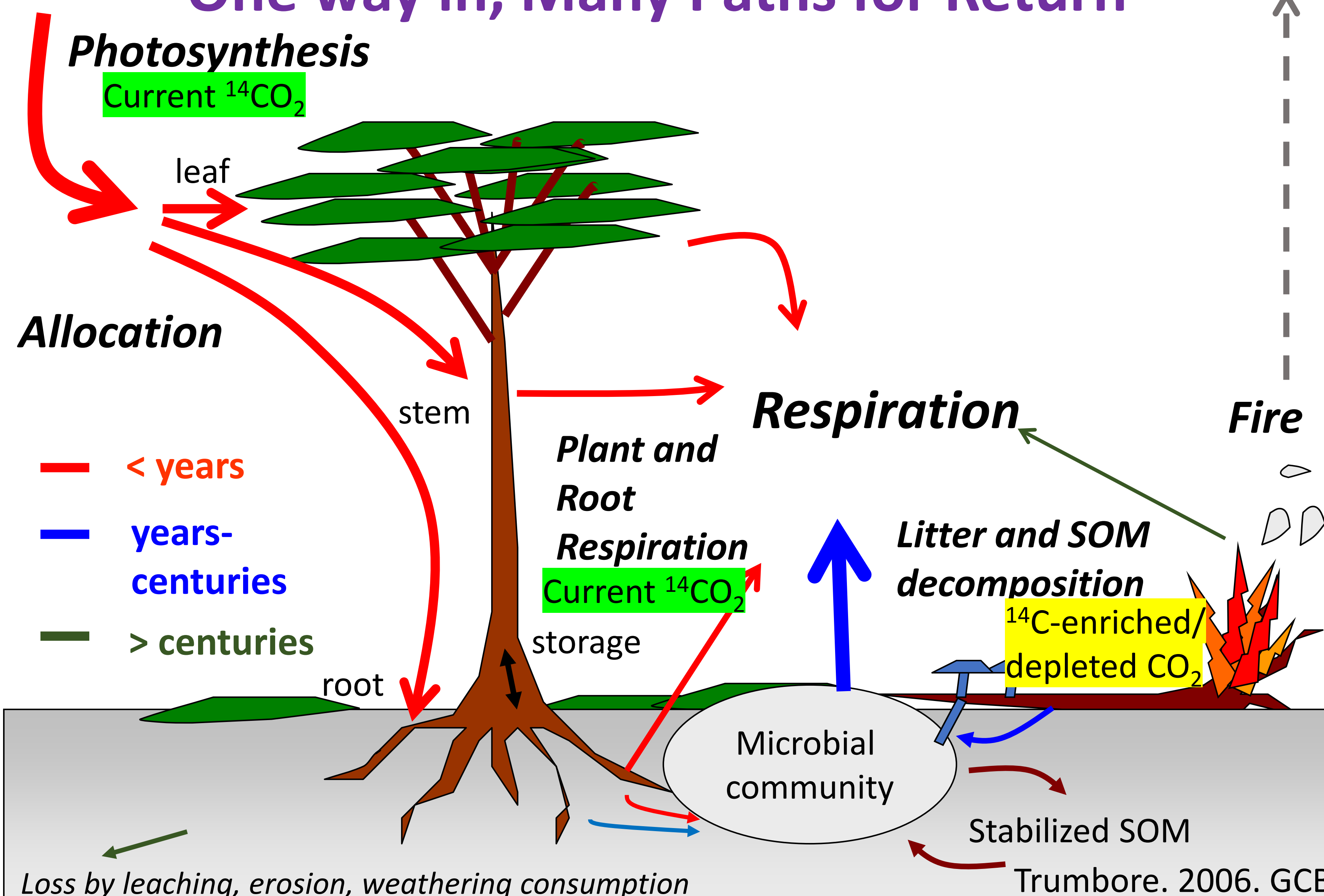
How Can We Quantify the Land C Sink?

Land-atmosphere CO_2 exchange (Net Ecosystem Exchange) & Remote sensing



Vegetation and soil C inventories

Carbon Flow in Terrestrial Ecosystems: One way in, Many Paths for Return



Big Questions in Terrestrial C Cycle Research

How productive is the terrestrial biosphere, and
how resilient are terrestrial ecosystems to changes in atmospheric CO_2, climate, and disturbance?

- How do plants allocate C above- and belowground?
- What is the make-up of future plant communities?

How much C is in terrestrial ecosystems, and
how vulnerable is it to changes in climate, disturbance, and land use?

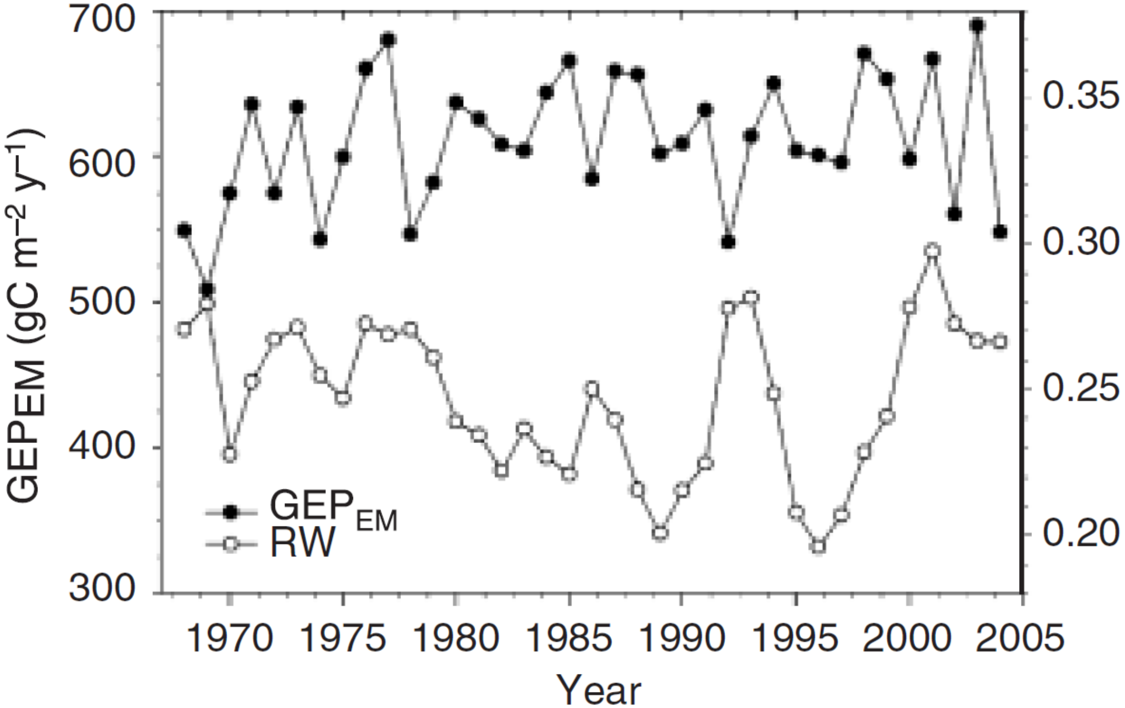
- Why and how fast does C accumulate in soils and how rapidly can it be re-mobilized?
- On what time scales will soil formation limit plant species migration?

How productive is the terrestrial biosphere, and how resilient are terrestrial ecosystems to changes in atmospheric CO_2, climate, and disturbance?

How do plants allocate C above- and belowground?

C Uptake and Tree Growth in a Boreal Forest

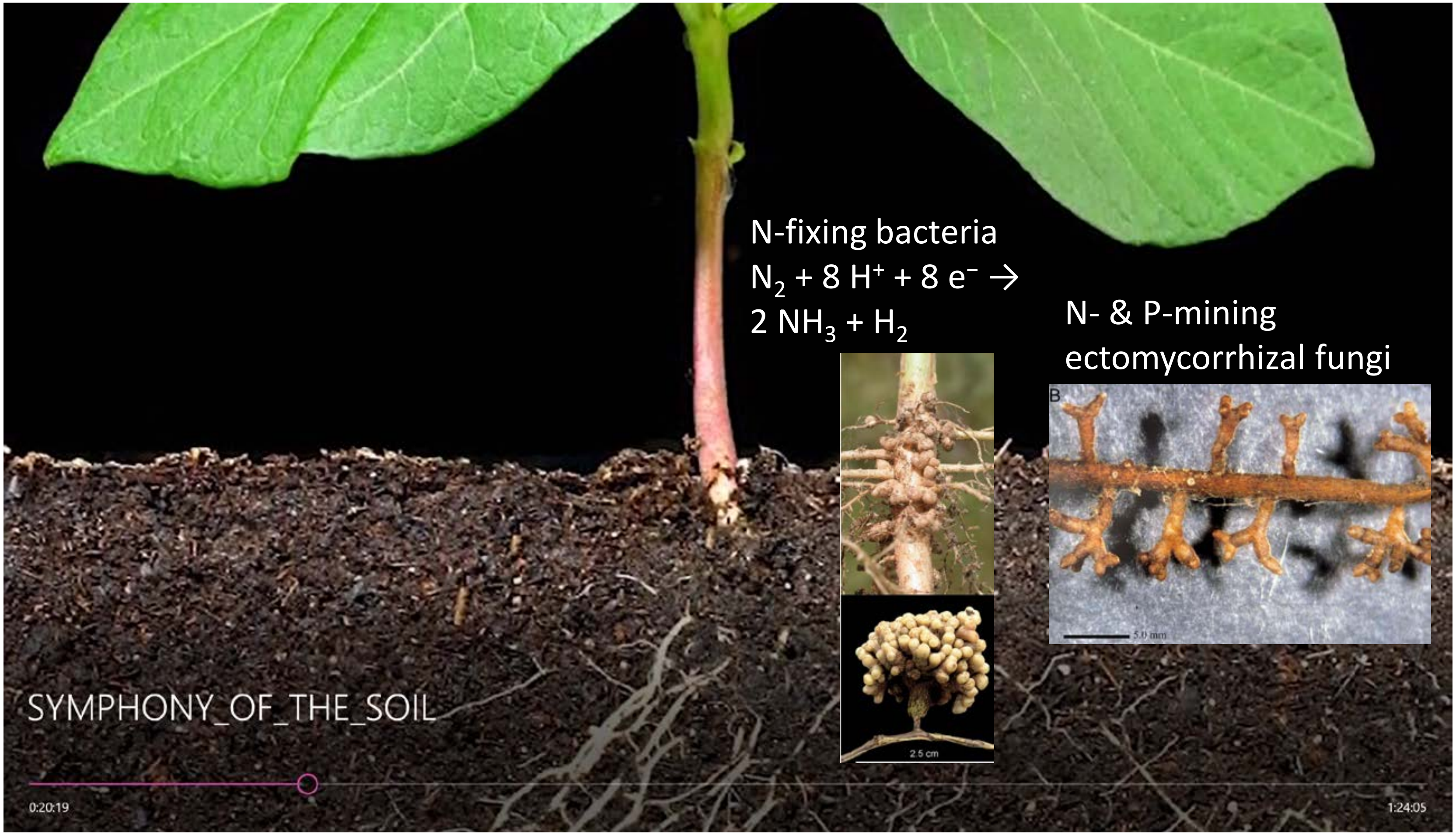
"The lack of relationship between ring width and gross ecosystem productivity (canopy-scale photosynthesis) may indicate that ring growth is controlled almost entirely by something other than C uptake."



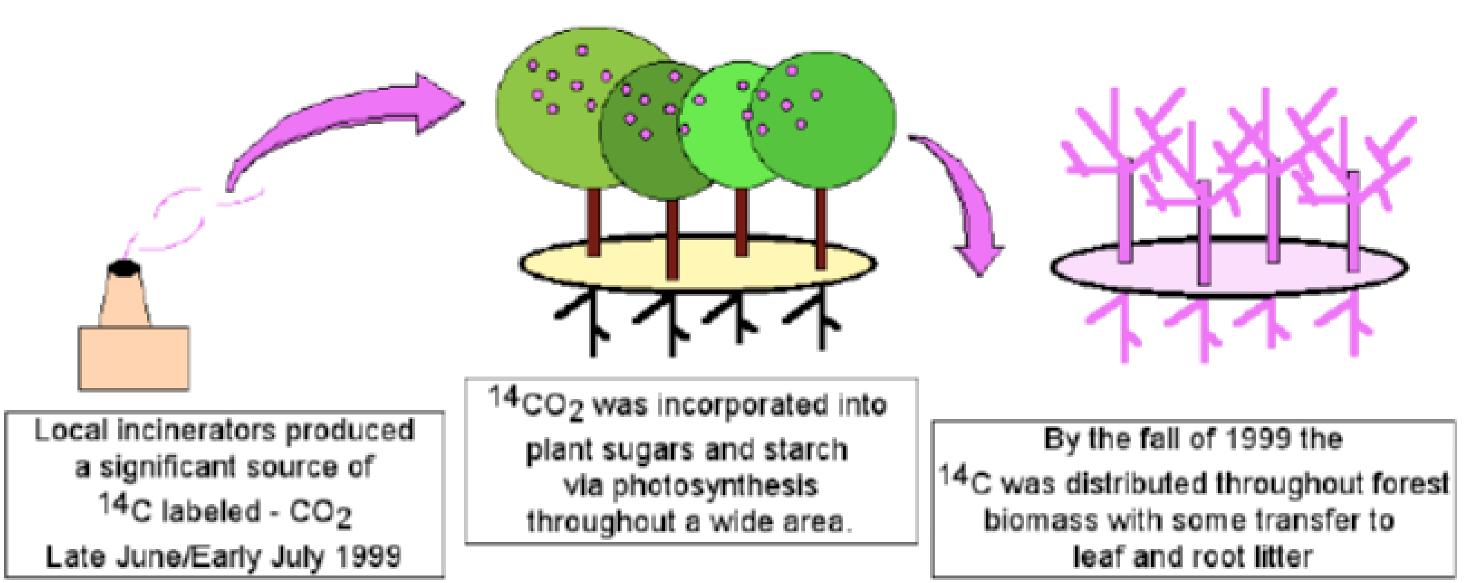
Rocha et al. 2006. Global Change Bio

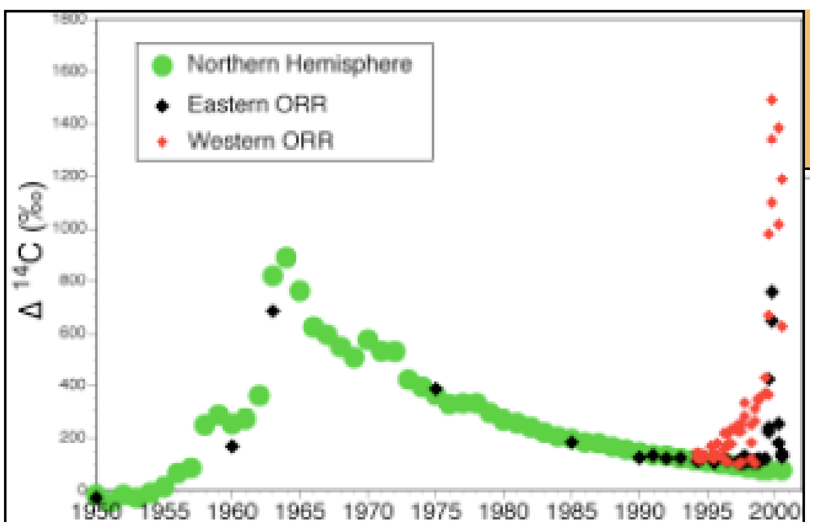
Where did the remaining assimilated C go?

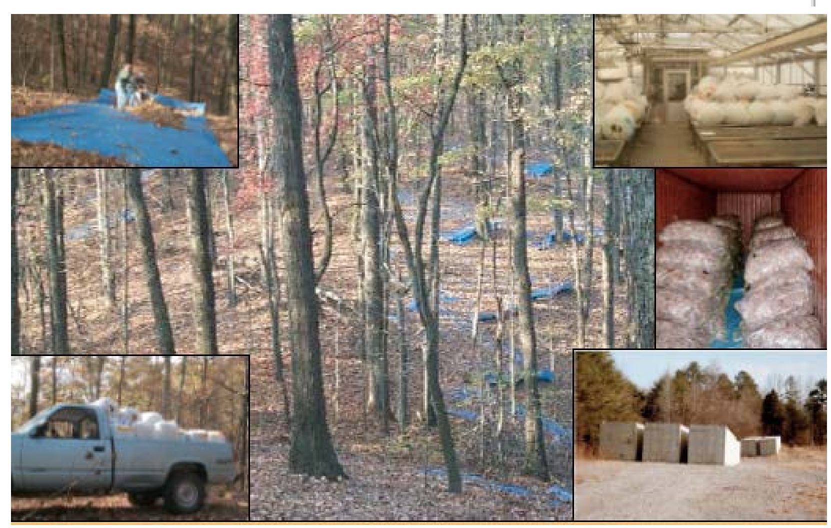
A lot of C is used to Feed Soil Microbes via Root Exudation



Enriched Background Isotope Study (EBIS)
An opportunistic ^{14}C-labeling study

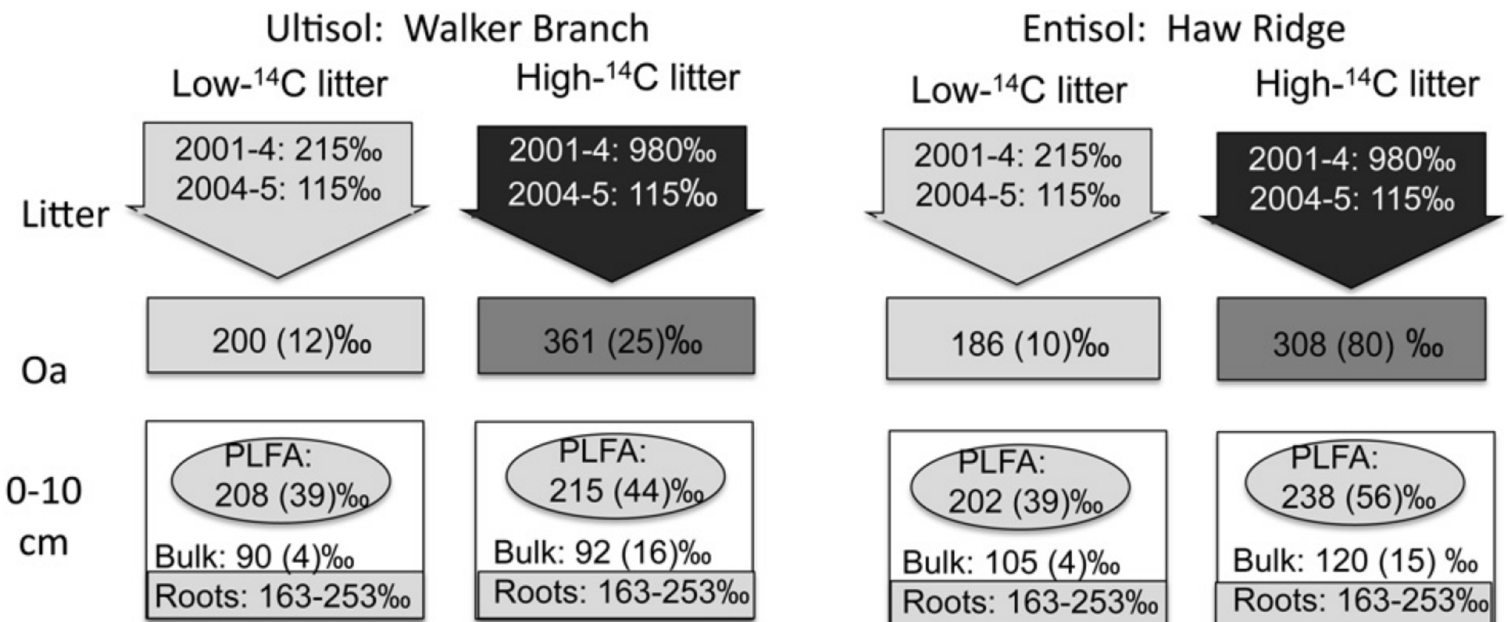


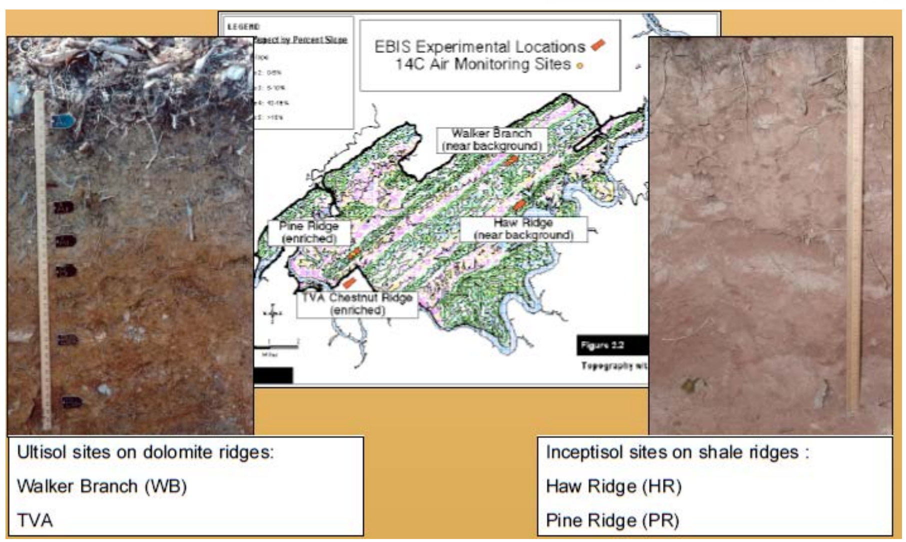




http://ebis.ornl.gov/HansonP1.pdf

Root-derived C (>60%), not recent (<4 yr old) leaf litter (<6%), is the major source of microbial C in a temperate forest mineral soil





Kramer et al. 2010.
Soil Bio Biochem

http://ebis.ornl.gov/HansonP1.pdf

C Allocation in Boreal Black Spruce Forests

Label application

1. Bicarbonate solution
2. Acidified to release CO_2
3. Circulated $^{14}CO_2$ through dome enclosure 1 hour
4. Produced a $\Delta^{14}C$ signature ~100,000 ‰

Chasing a ^{14}C Pulse over 4 hours to 30 days

Measurements of the CO_2 flux and isotopic content ($\Delta^{14}C$) of dark respiration

1. Soil Surface
- Moss and grass
- Roots
- Soil

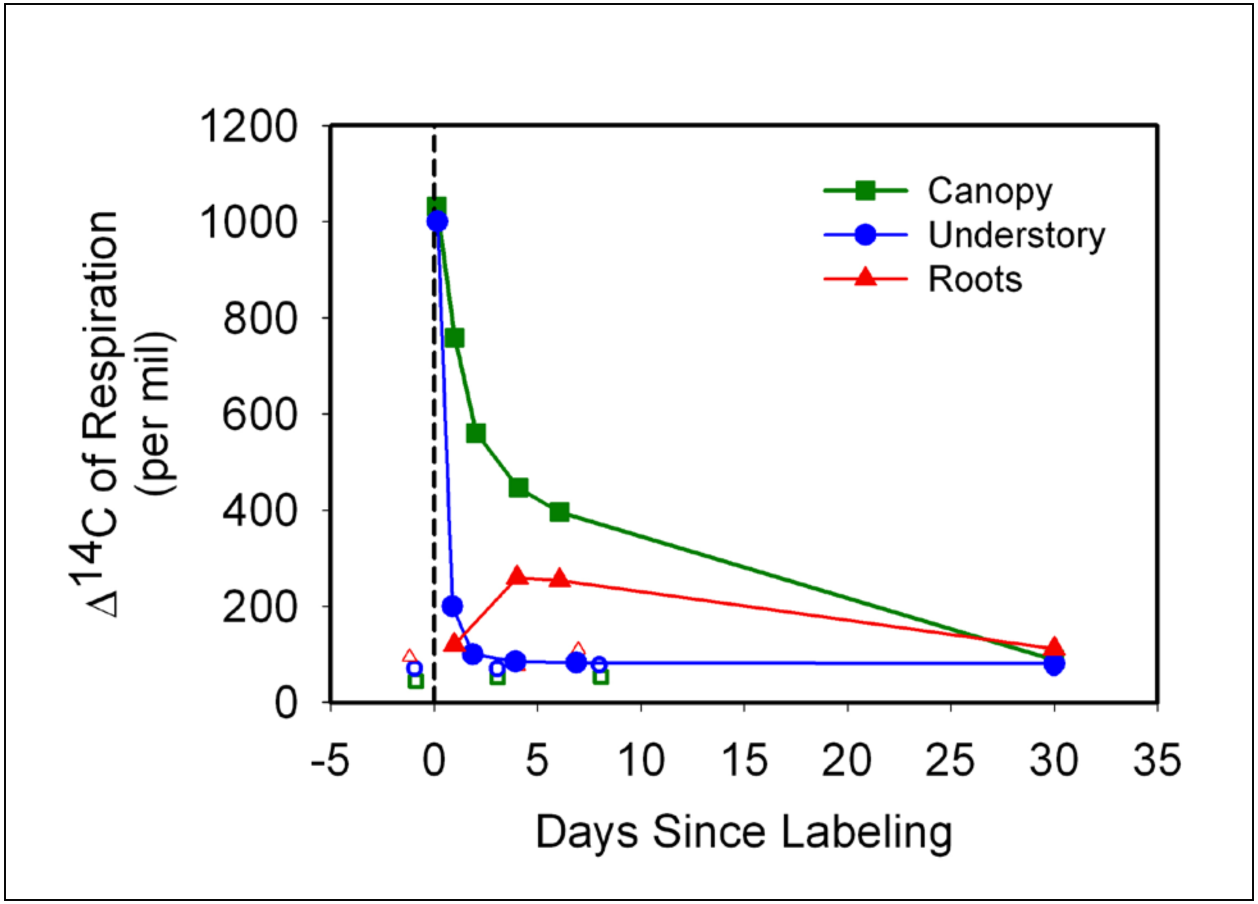
2. Canopy
- Needles
- Stems

3. Ecosystem

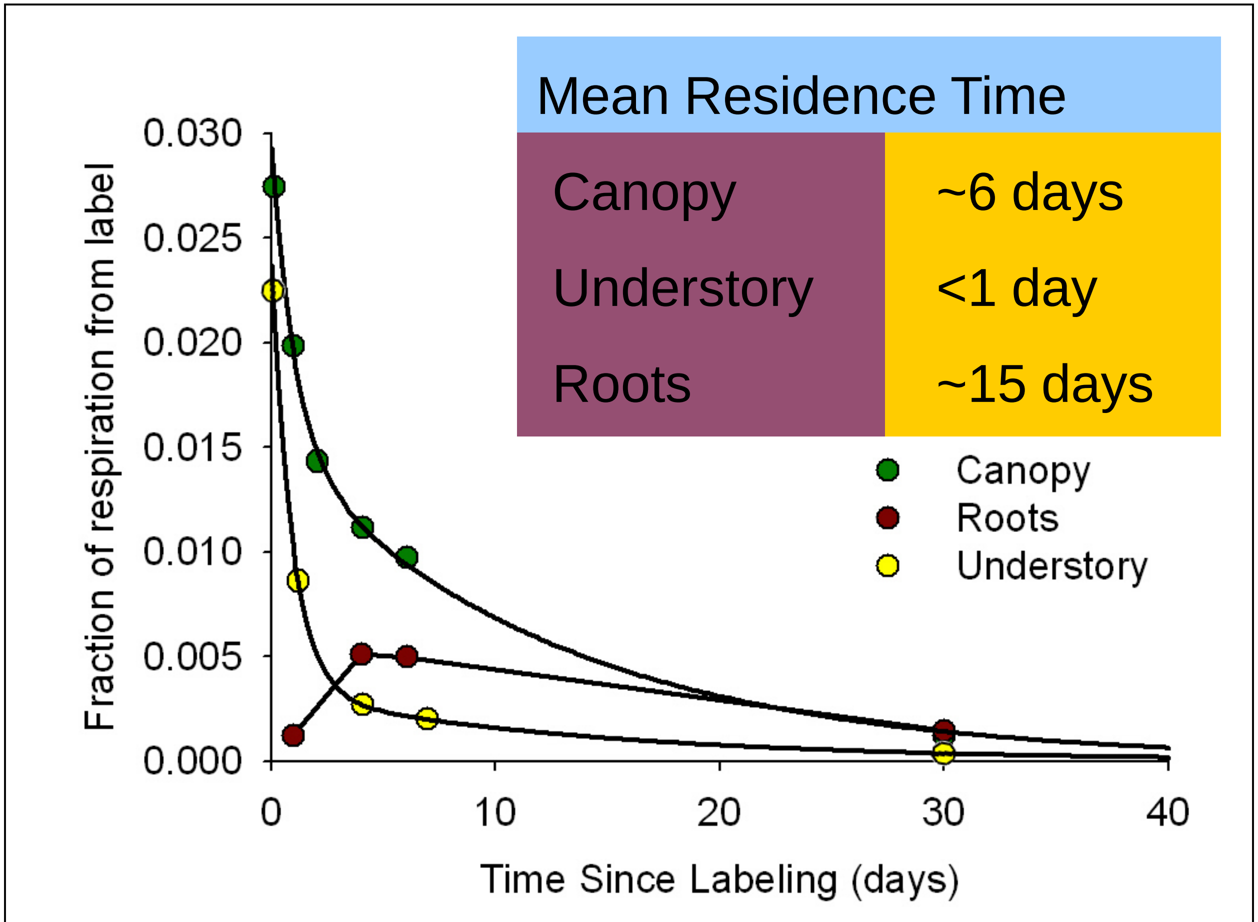
4. Incubations
- Excised roots
- Moss and grass

5. Soil gas
- Multiple depths

$\Delta^{14}C$ in Respiration



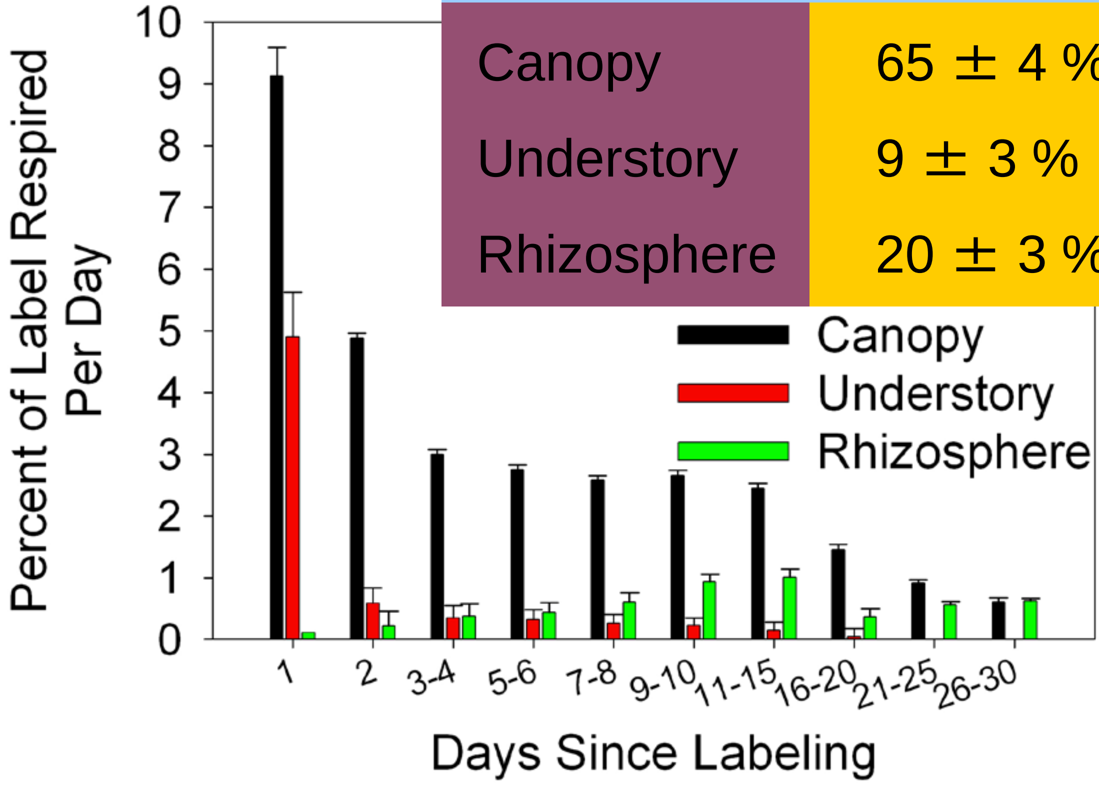
Timing of Label Respired



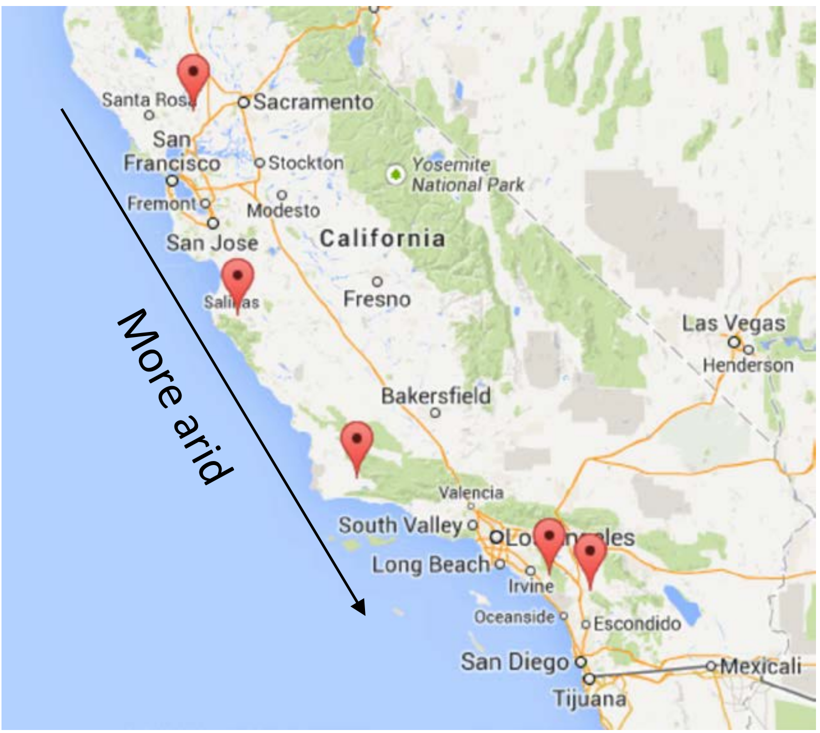
Mean Residence Time	
Canopy	~6 days
Understory	<1 day
Roots	~15 days

Allocation of Label:
¾ Respired Aboveground

Allocation	
Canopy	65 ± 4 %
Understory	9 ± 3 %
Rhizosphere	20 ± 3 %



How do Trees Allocate C in relation to Life Strategy and Climate?



Sympatric deciduous and evergreen oaks, CA

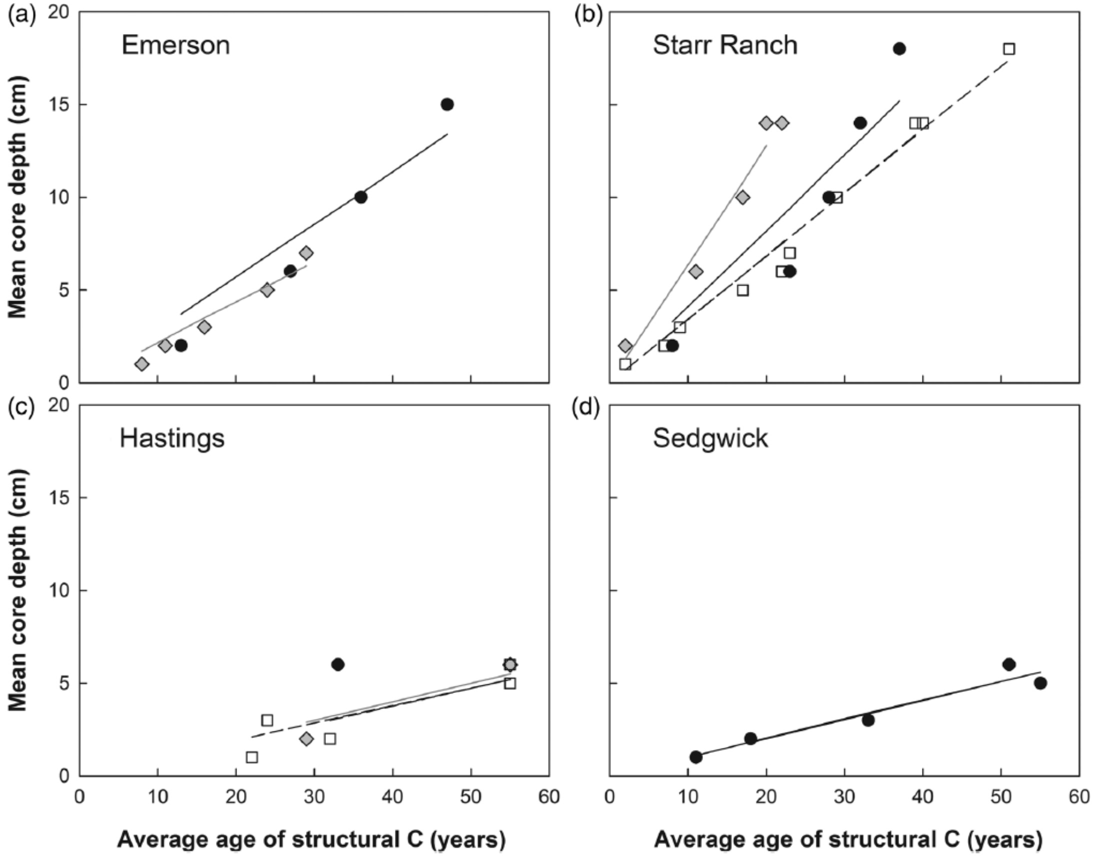
Extraction of tree cores

Sampling stem CO_2 efflux

Muhr et al. 2013. Tree Phys
Trumbore et al. 2013. New Phyt

Growth Rates of Oaks Across their Range

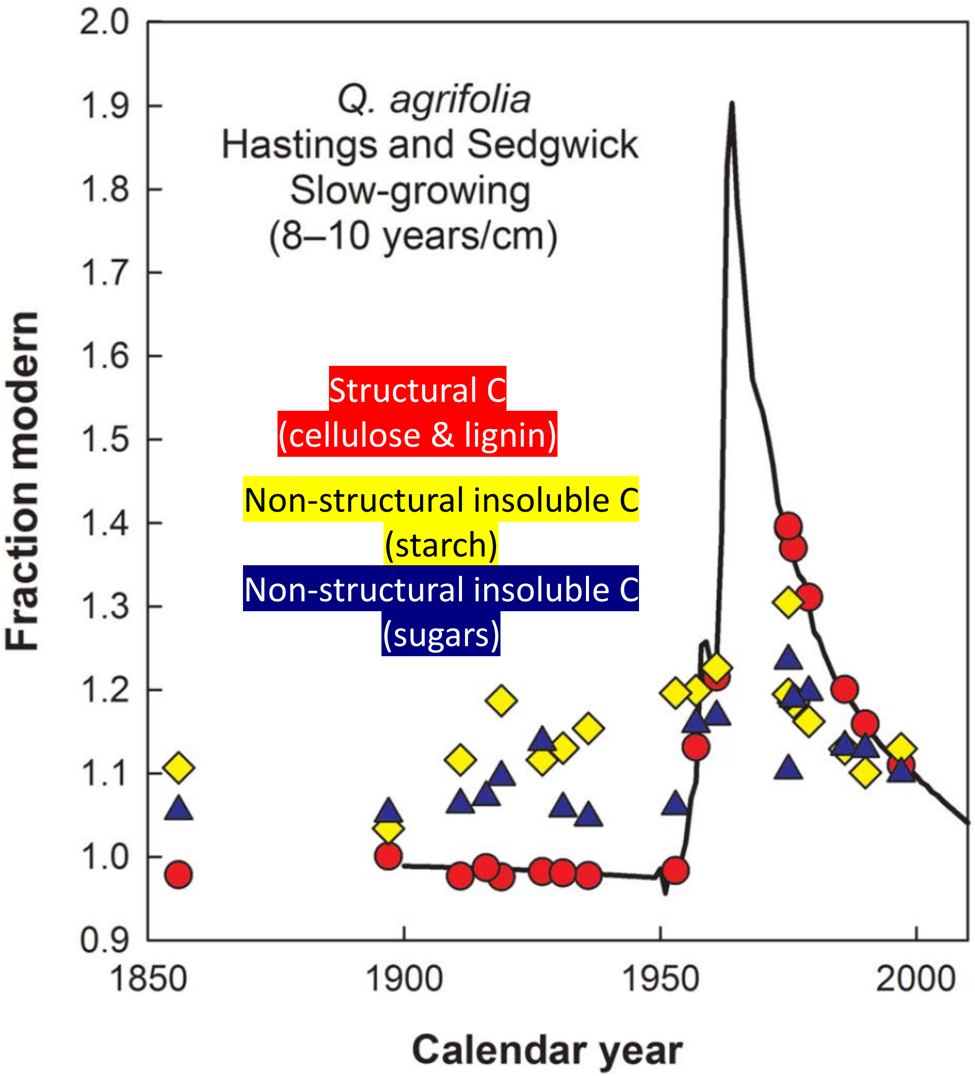
Evergreen *Q. agrifolia*



Growth rates ranged from 0.04 to 0.6 cm yr^{-1}

Oaks grew faster at the more southern (drier) locations of each species

^{14}C of Wood vs. Sugars & Starch (nonstructural C) in Mediterranean Oaks



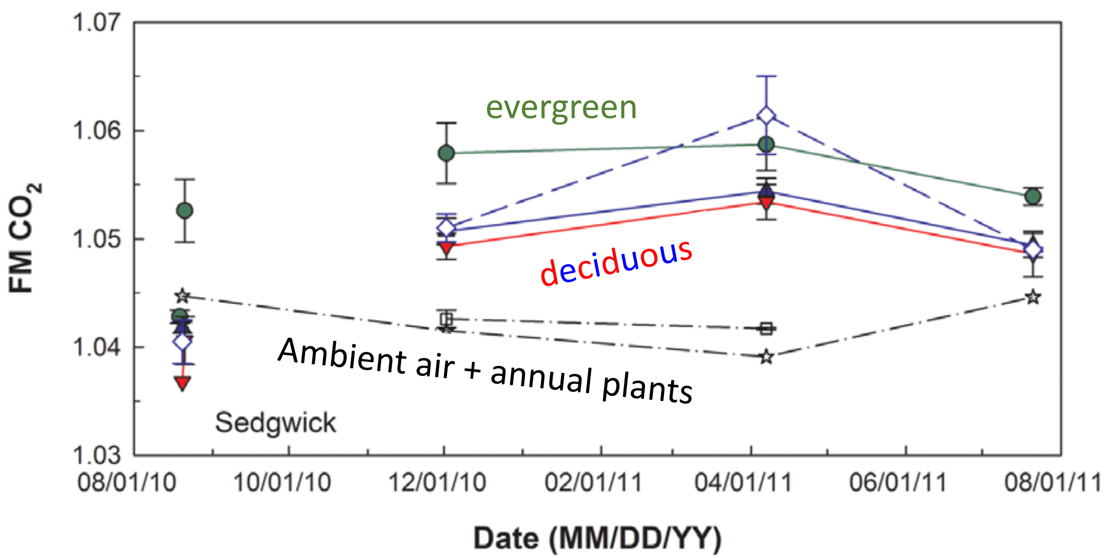
In all oak species, nonstructural C was younger than the structural material from which it was extracted

No obvious differences in soluble nonstructural C concentrations between species, life strategies or locations

Higher concentrations of insoluble nonstructural C in evergreen oaks

Trumbore et al. 2015. Tree Phys

C dynamics in Mediterranean oak trees
^{14}C of Wood vs. Sugars & Starch



Trumbore et al. 2015. Tree Phys

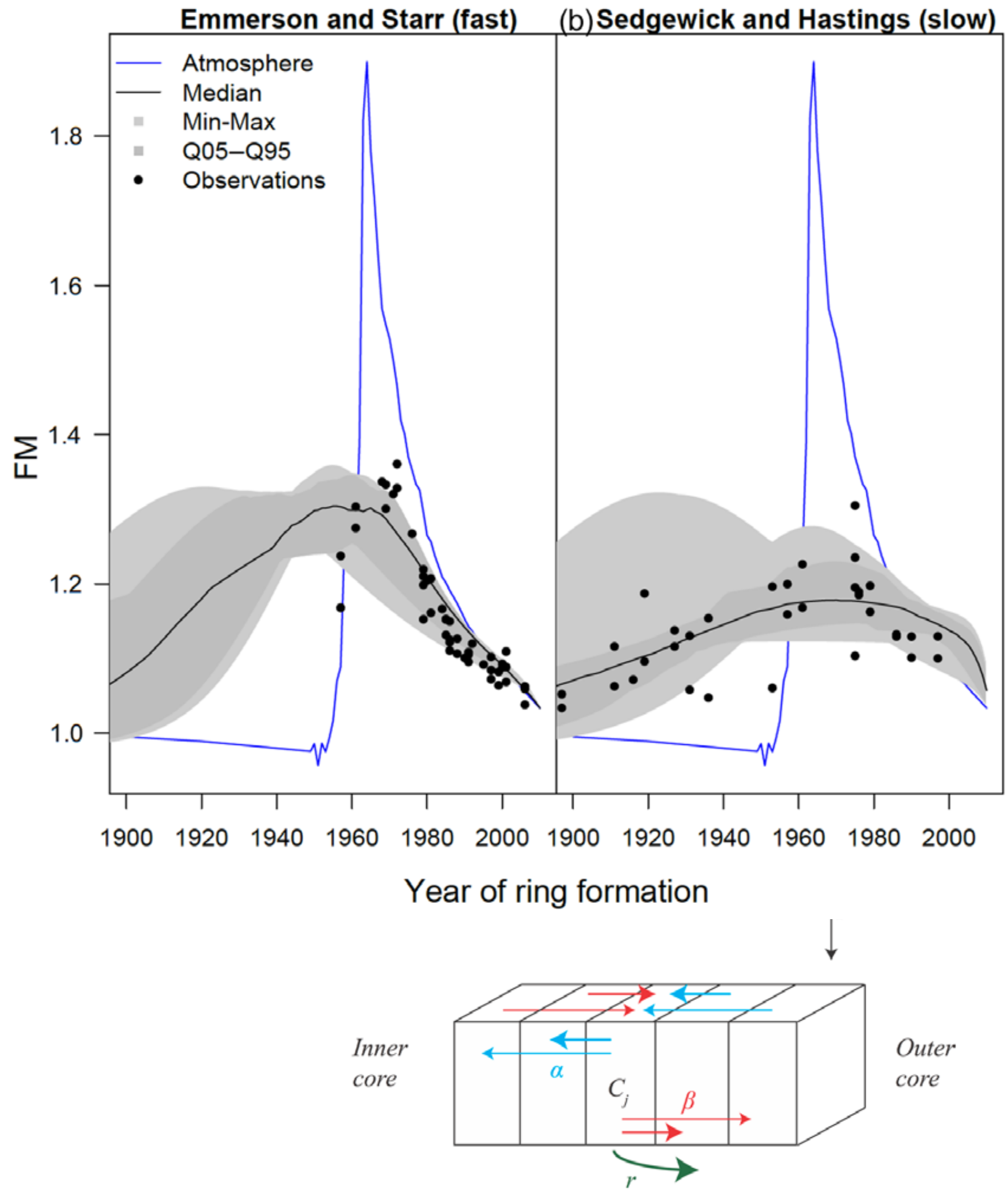
Stem-emitted $^{14}CO_2$ was enriched relative to ambient $^{14}CO_2$, more in evergreen than deciduous oaks

C source of CO_2 emissions:
2–4-year-old C in evergreen
1–2-year-old C in deciduous

Oaks

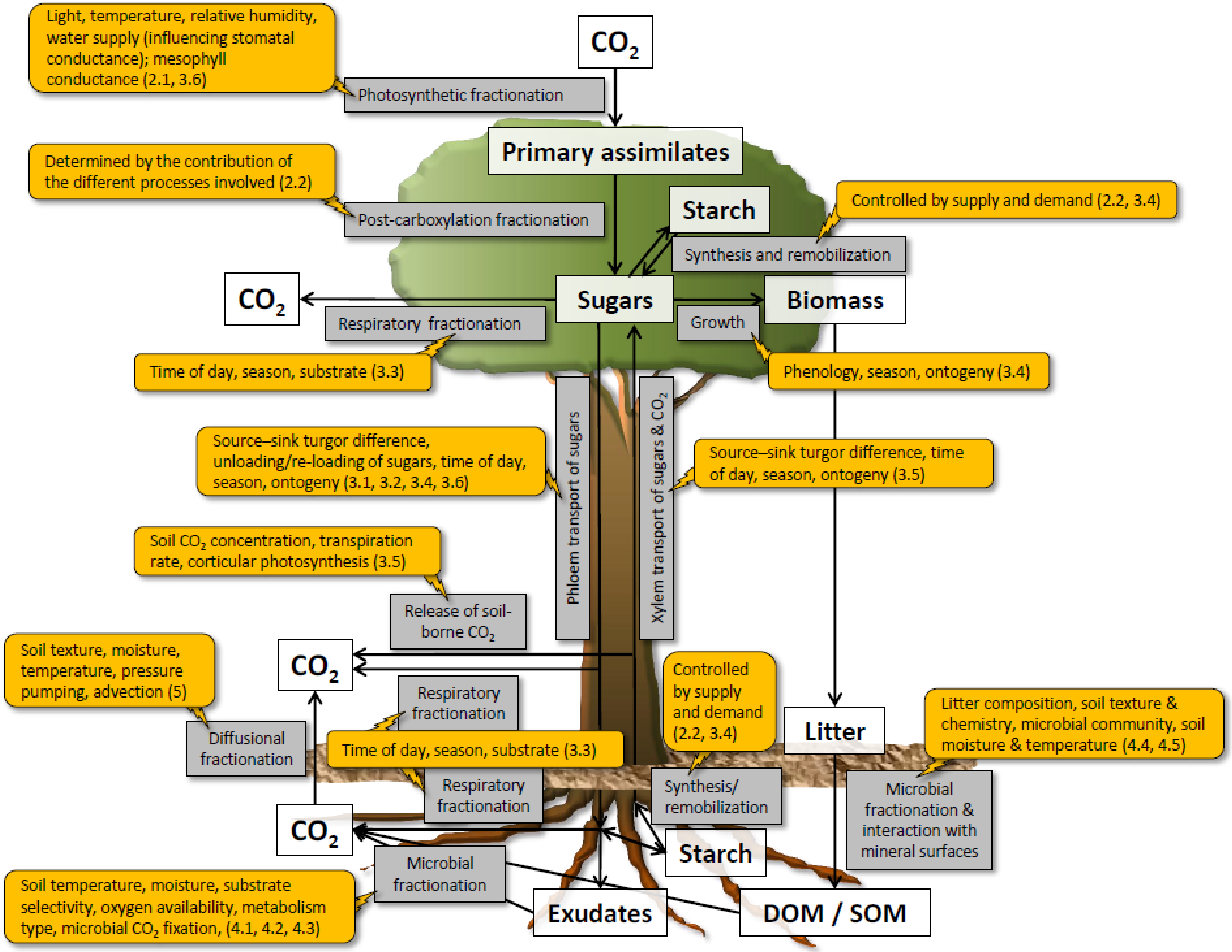
Across the oaks' range, not climate, but "vigor" (growth rate) largely controlled the size, age and allocation of nonstructural C pool, faster-growing trees respired more and stored (by inward mixing) less of their nonstructural C

Mature trees accumulate years-to-decade-old nonstructural C across a wide climatic range (tropical, Mediterranean and temperate) to fuel respiration and recovery



Trumbore et al. 2015. Tree Phys

Emerging Picture of Plant C Allocation



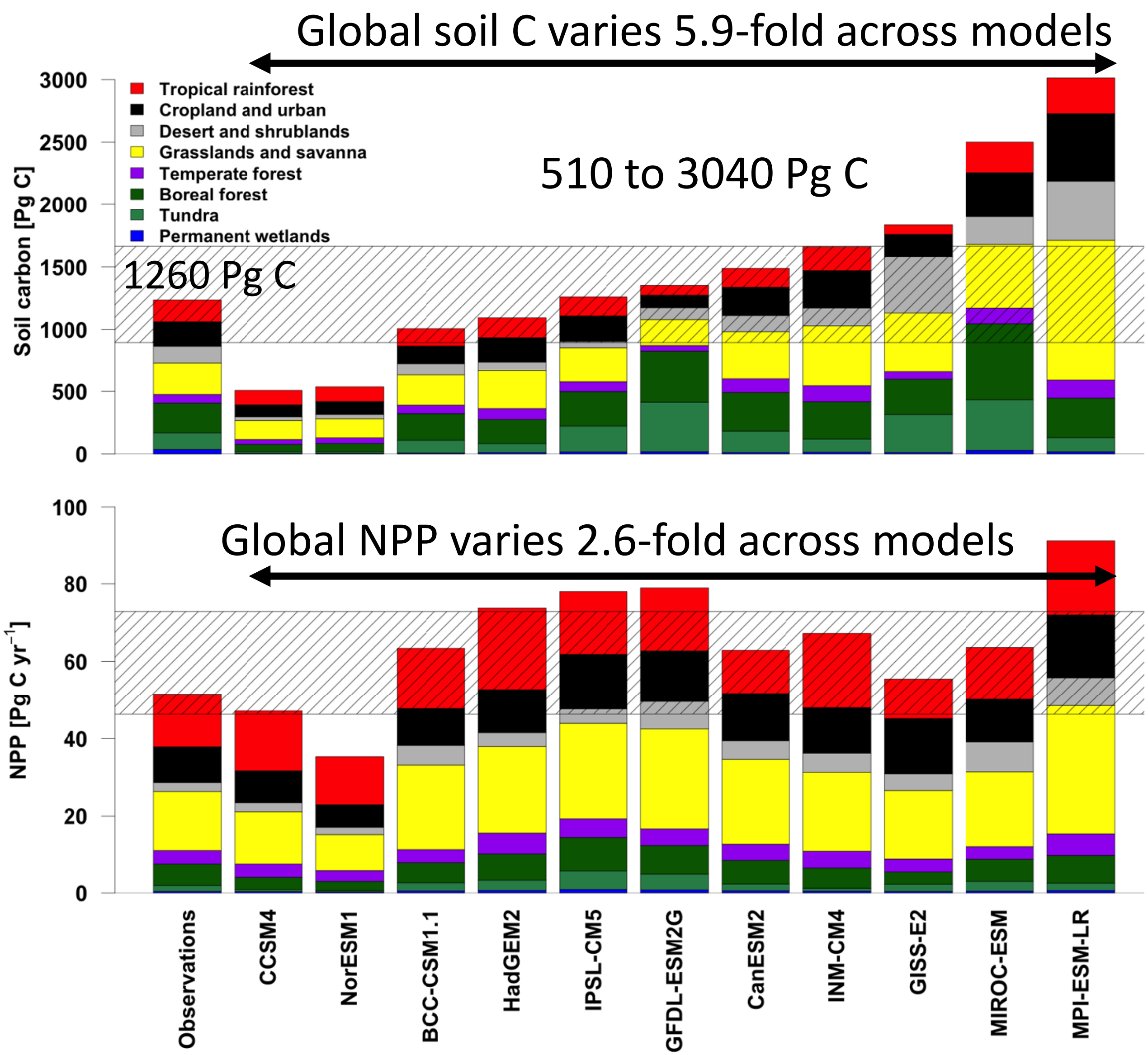
Brueggemann et al. 2011. Biogeosci

How much C is in soils?
Where are large soil C stocks?

How much C is in terrestrial ecosystems, and how vulnerable is it to changes in climate, disturbance, and land use?

Why and how fast does C accumulate in soils and how rapidly can it be re-mobilized?

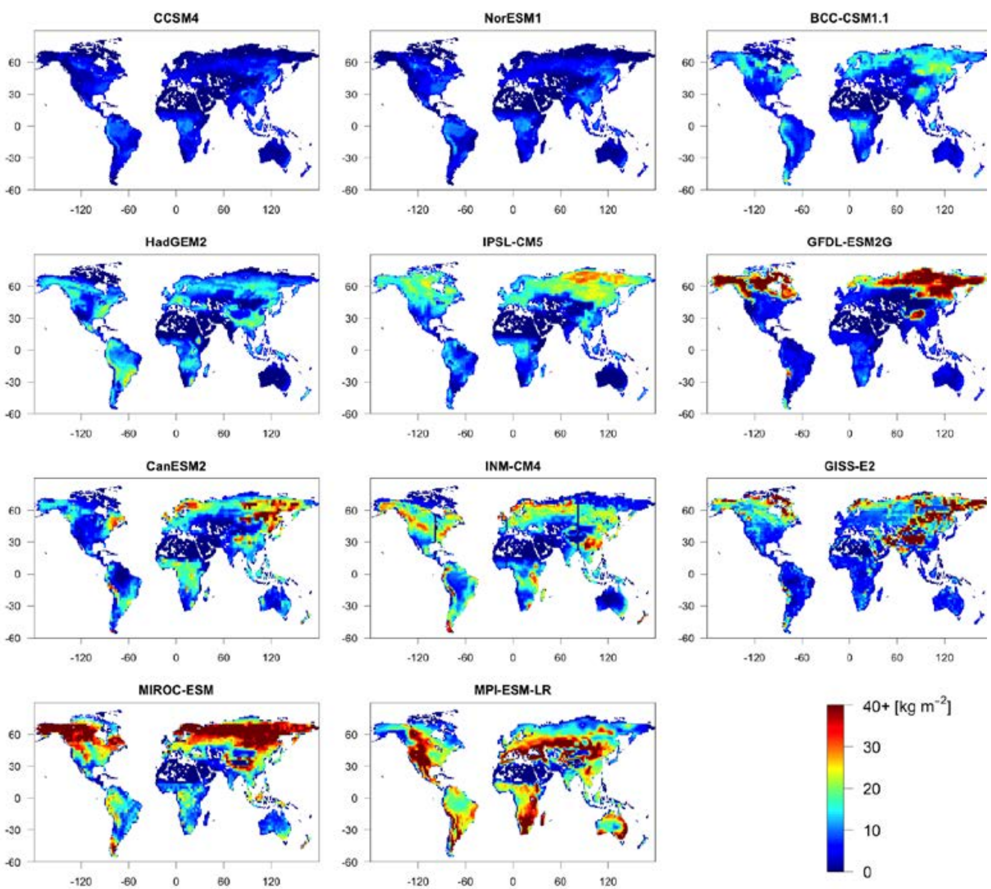
How much C is in Soils?



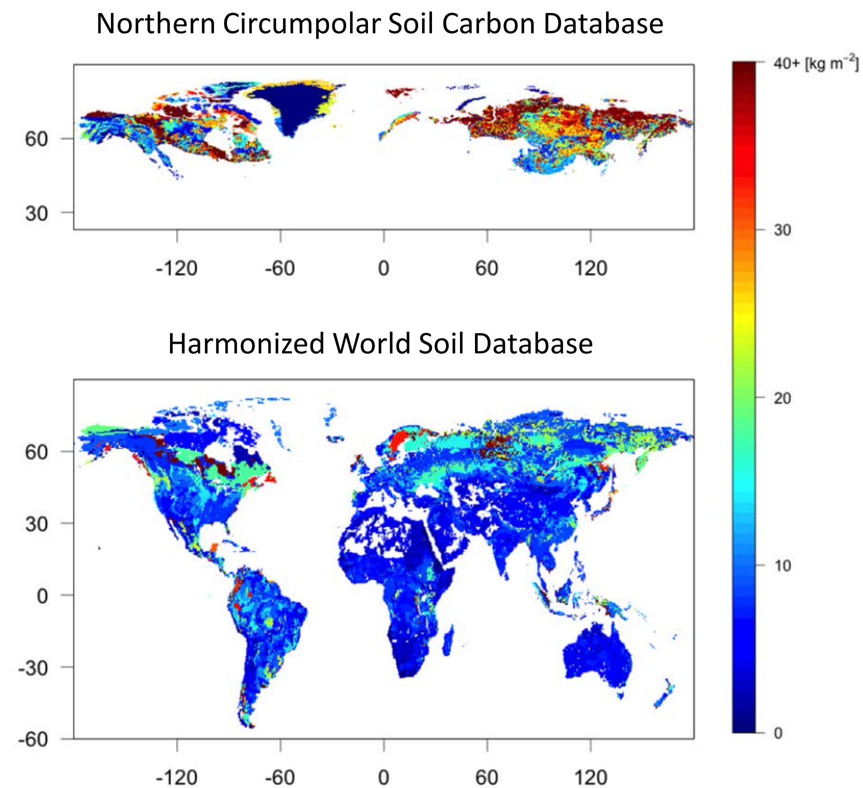
Todd-Brown et al. 2013. Biogeosci

Where is Soil C?

C density simulated by 11 Earth System Models



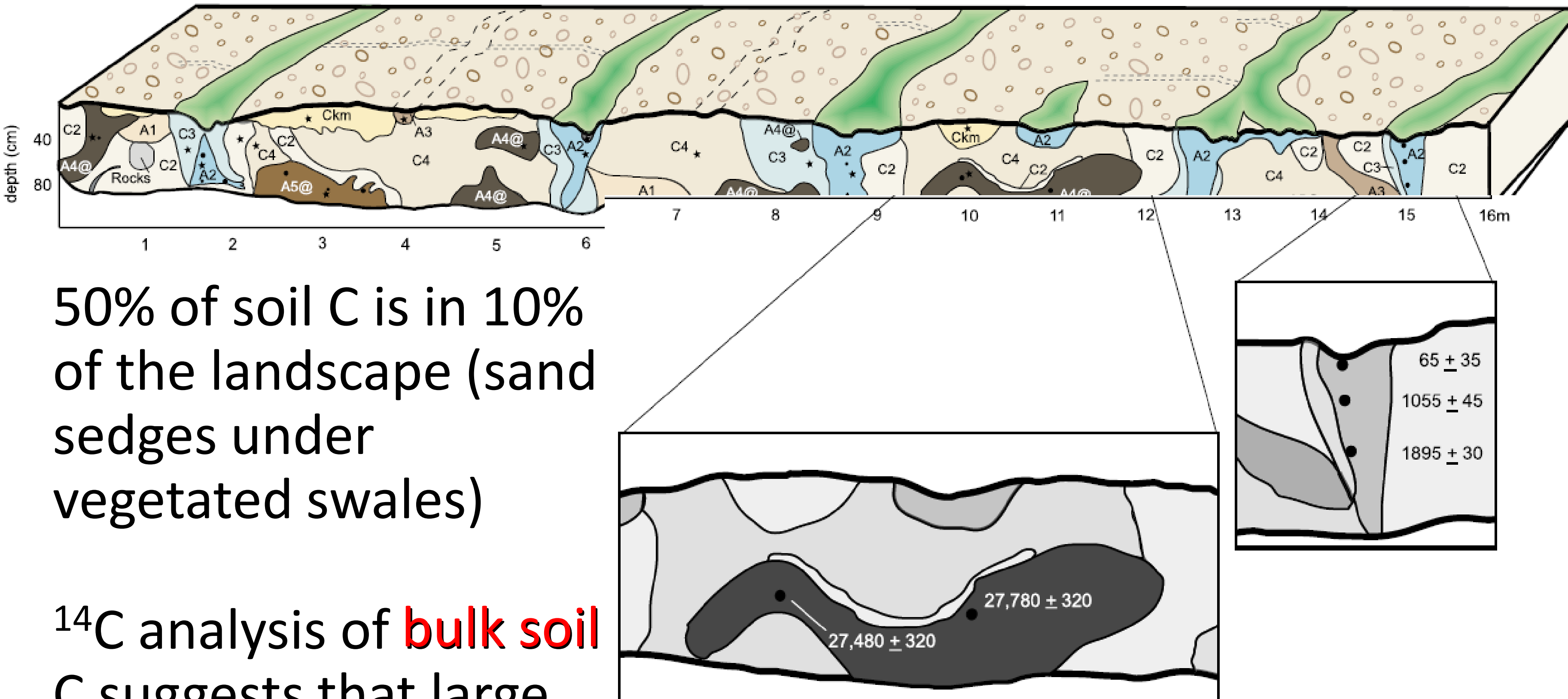
Observed C density



Todd-Brown et al. 2013. Biogeosci

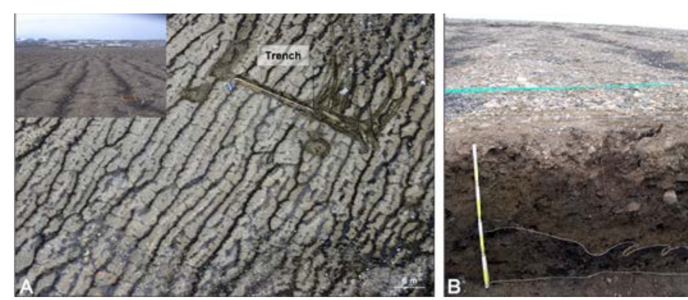
Soils ~~can be~~ are Complicated

High Arctic
Gelisol, Thule, NW Greenland



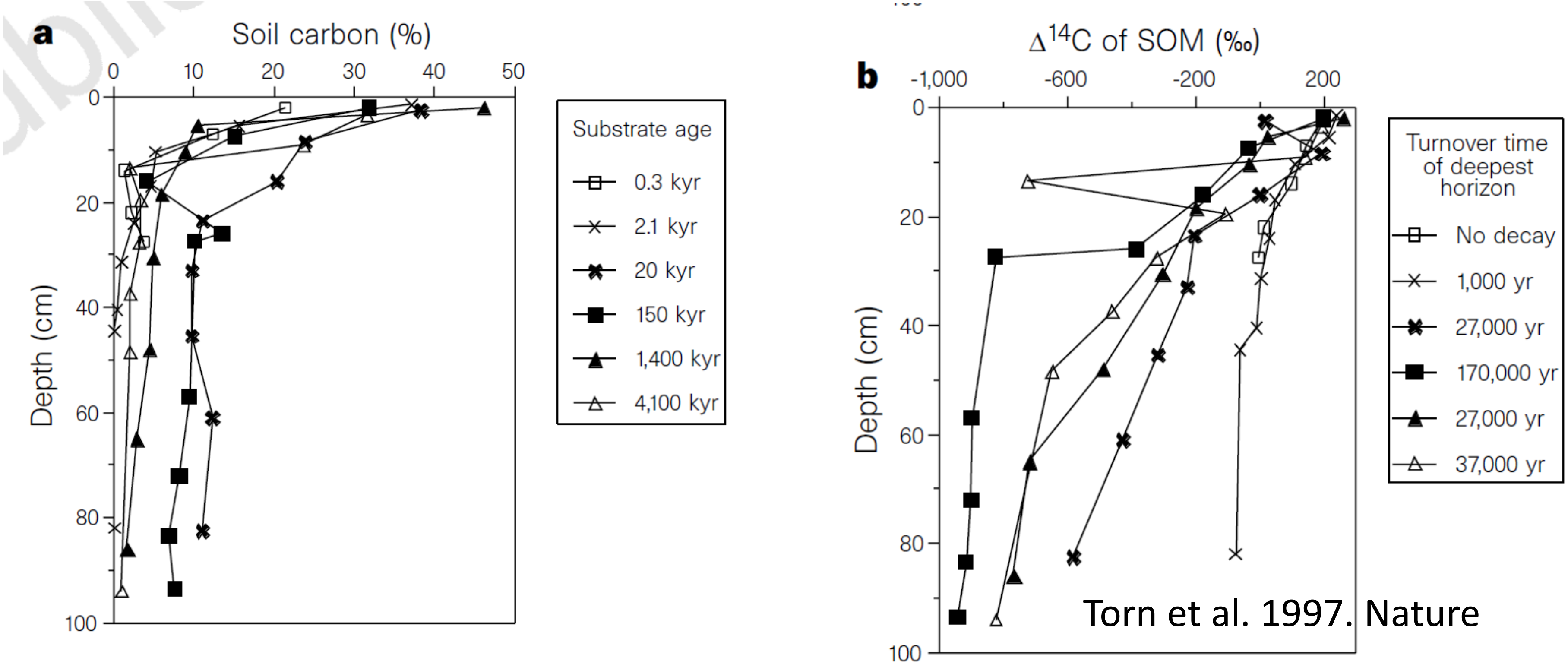
50% of soil C is in 10% of the landscape (sand sedges under vegetated swales)

^{14}C analysis of **bulk soil** C suggests that large proportion of soil C is not derived from current vegetation



Horwath et al. 2008. J Geo Res

Typical soils: C stocks decline and become older with depth; mineral composition matters

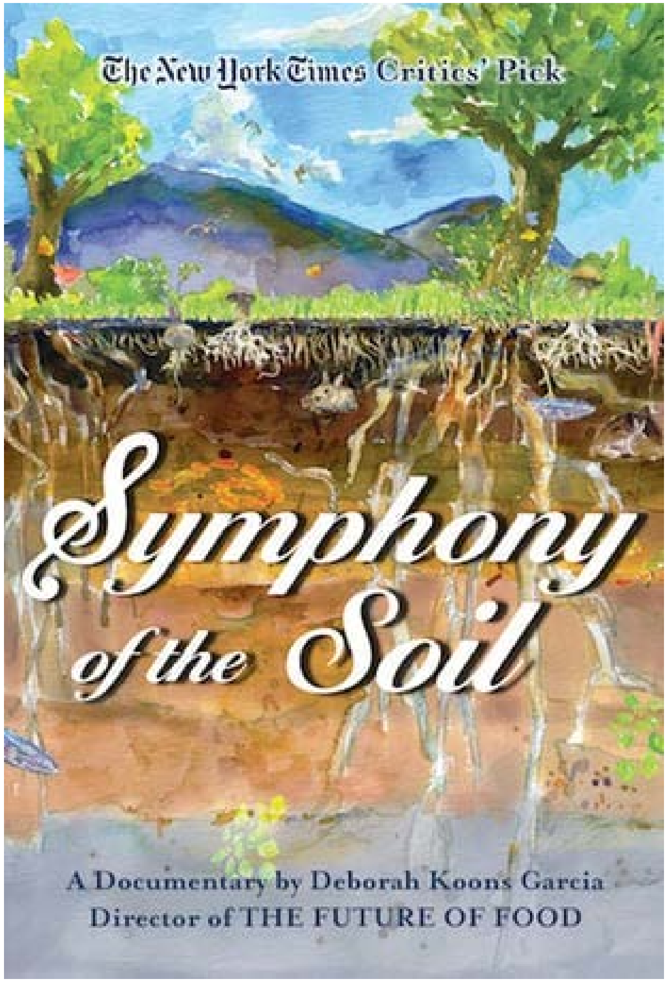


Torn et al. 1997. Nature

In volcanic soils, metastable shortrange-order minerals (allophane) provide a mechanism for long-term stabilization of organic matter in soils.

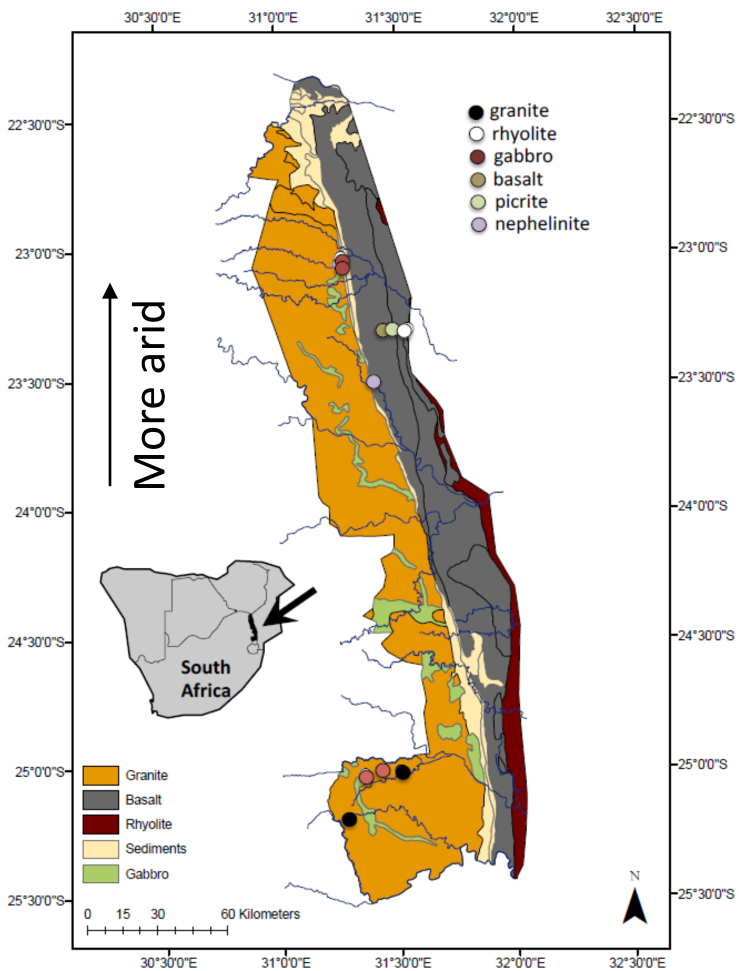
The soil's ability to accumulate C increases during the first 150 kyr of soil development as the parent material weathers to metastable, non-crystalline minerals. Thereafter, the amount of non-crystalline minerals declines, more stable crystalline minerals accumulate, and the soil's C content decreases by 50% over the next 4 Myr.

“After soils are born, they have a life…”



Chronosequence of soil development on the Hawaiian Archipelago

In ancient felsic soils, mineralogy is the most important explanatory factor for C content (crystalline Fe) and turnover time (amount of smectite)



Bulk soil is a complex mixture of C that cycles between the atmosphere and the land on very different time scales

Carbonate-free bulk
%C = 1.94% 100% C_T
δ^{13}C= -14.9 ‰
Δ^{14}C = -16‰ (TT = 385 y)

SPT (1.7 SG)

Flotation, 2% H_2O_2

Non-clay (includes LF)
%C = 1.5% 63% C_T
δ^{13}C= -16 ‰
Δ^{14}C=-+149‰ (TT = 30 y)

Roots
δ^{13}C= -16.6 ‰
Δ^{14}C= +76‰

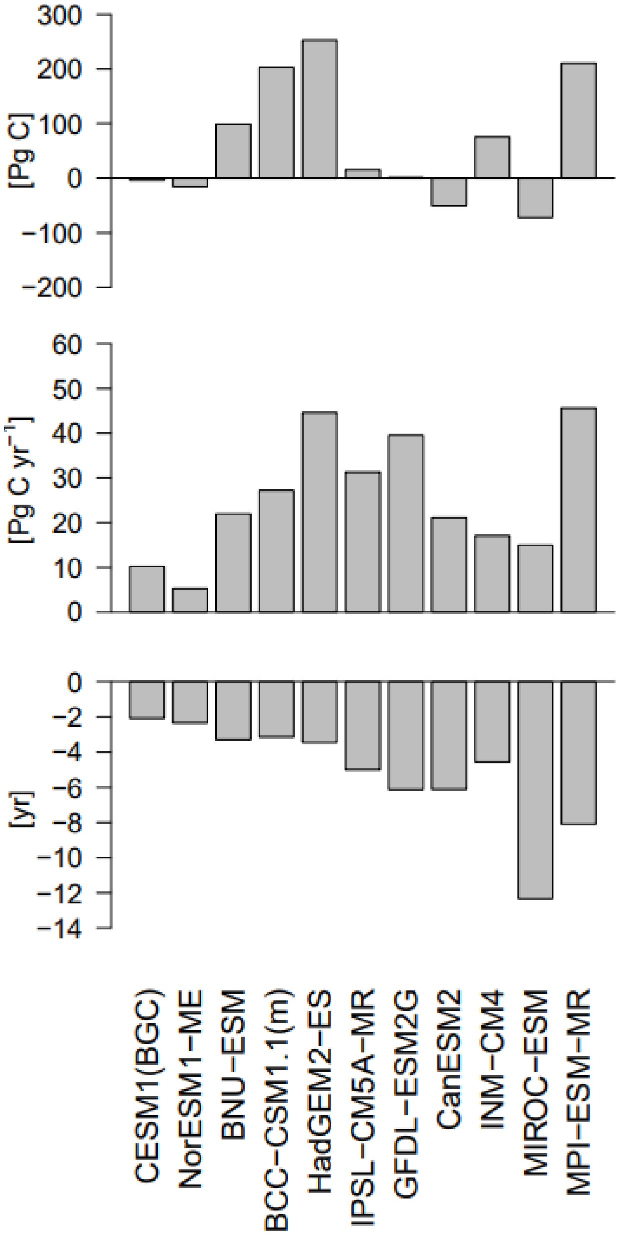
LF
%C = 11.6 % < 20% C_T
δ^{13}C= -16.6 ‰
Δ^{14}C = +60‰
(TT = 4,125y)

Clay
%C = 2.5% 47% C_T
δ^{13}C = -14.1 ‰
Δ^{14}C= -125‰ (TT = 1280 y)

HF (includes clay)
%C = 1.8 % 84 % C_T
δ^{13}C = -14.8 ‰
Δ^{14}C = -23‰ (TT = 425 y)

Khomo et al. 2017. Soil

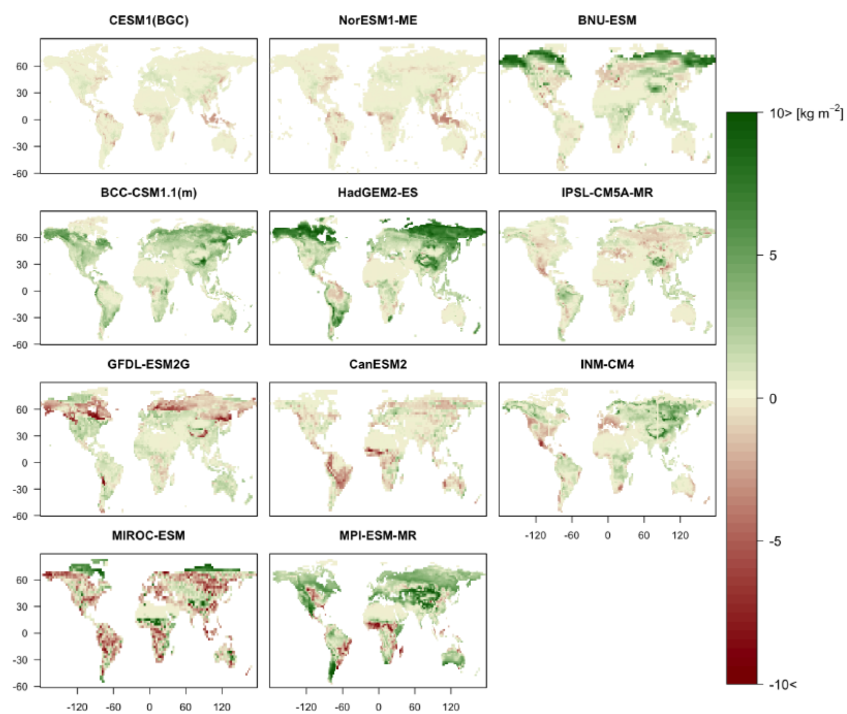
21st century absolute change in 11 Earth System Models



Land C sink 2100?

Predicted changes in soil C:
-20 to 360 Pg C or +30% C in 200 yrs

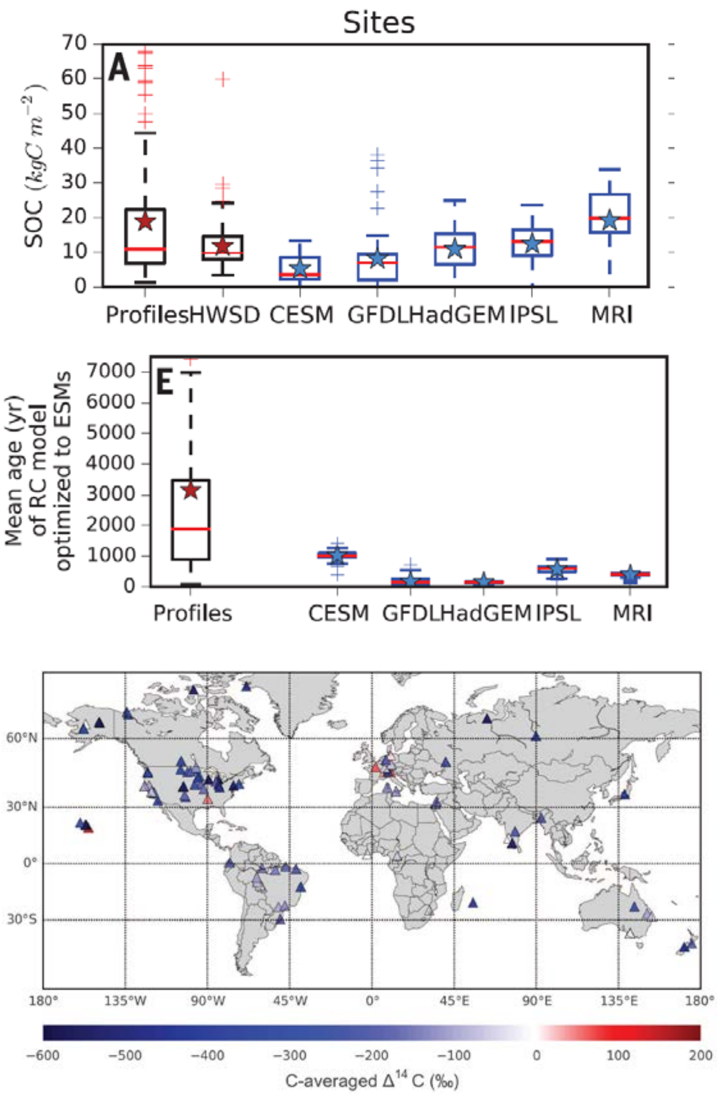
In coupled models, C-concentration feedback dominates, rel. sink strength (%-soil C change) depends mostly on rising atmospheric $CO_2 \rightarrow$ NPP $\rightarrow$ soil-C



Todd-Brown et al. 2014. Biogeosci

Land sink 2100?

Soil ^{14}C offers a constrain on future accumulation rates



Compared ^{14}C data from 157 globally distributed soil profiles (0-1 m) to soil C simulated by Earth System Models

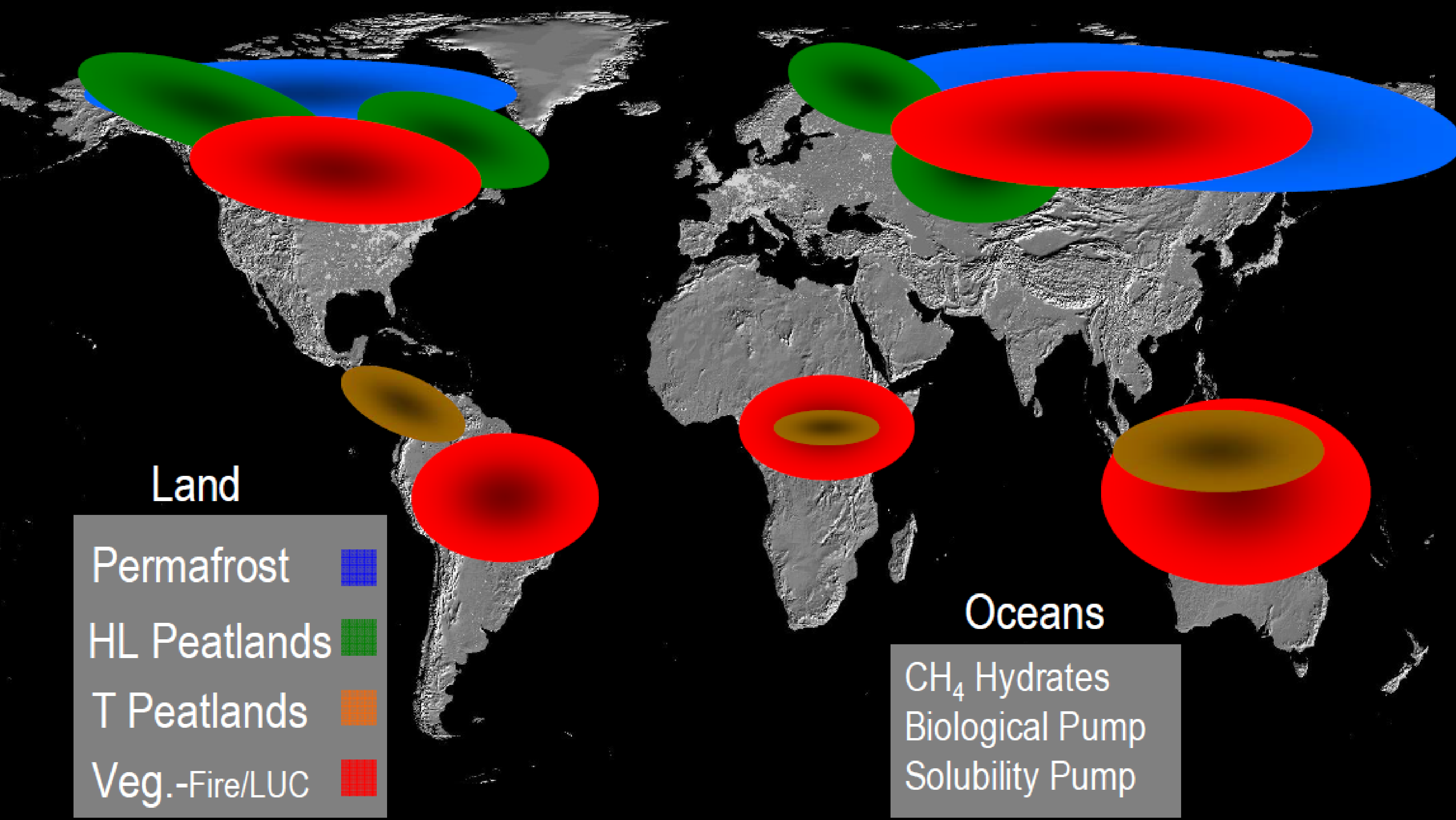
ESMs underestimated the mean age of soil C >6x (430 ± 50 vs. 3100 ± 1800 yrs)
→ ESMs overestimated C sequestration potential of soils 2x

ESMs must better represent C stabilization processes and the turnover time of slow and passive reservoirs when simulating future atmospheric CO_2 dynamics

He et al. 2016. Science

Vulnerability of the Carbon Cycle in the 21st Century

Hot Spots of the Carbon-Climate System

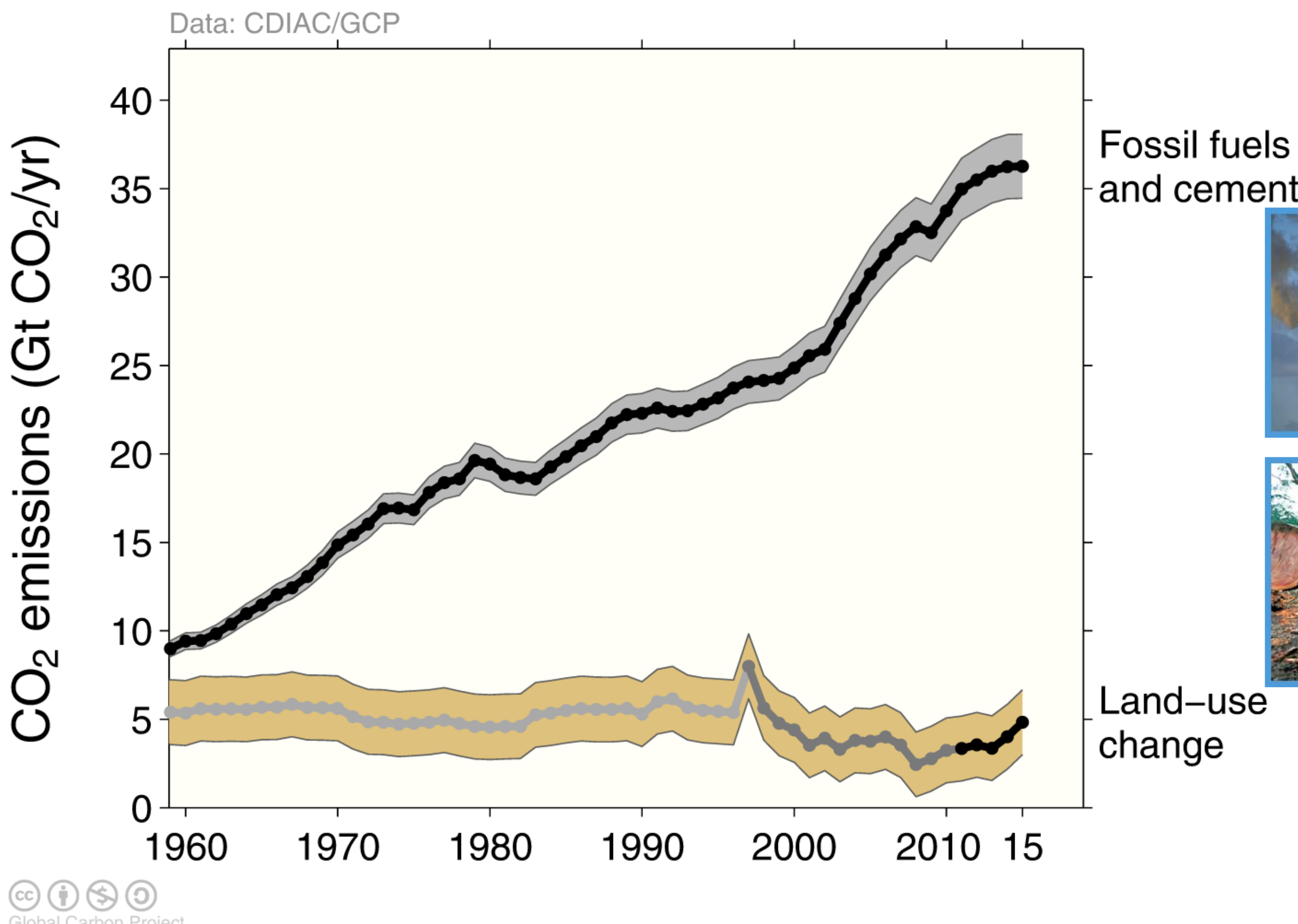


Canadell et al. 2007

Many Pools and Processes not included in Earth System models

Total global emissions

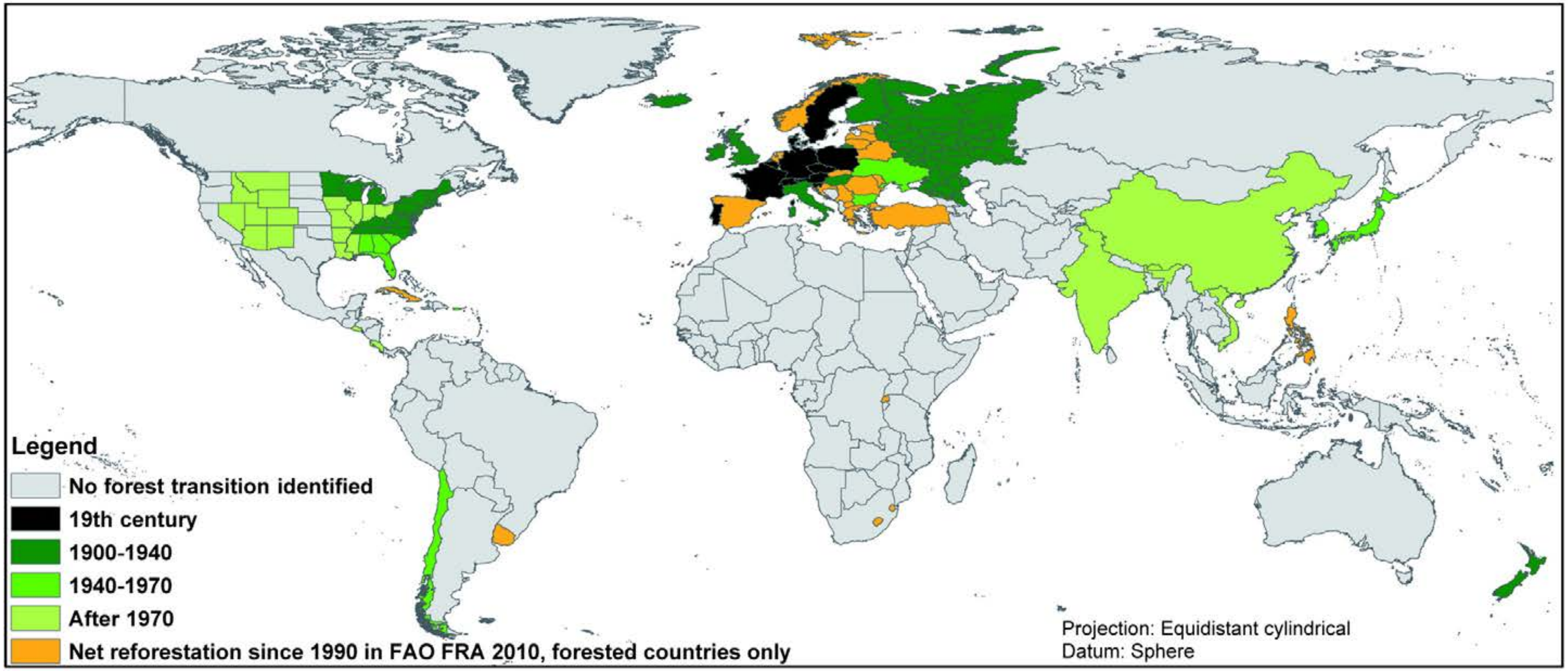
Total global emissions: 41.9 ± 2.8 $GtCO_2$ in 2015, 49% over 1990
Percentage land-use change: 36% in 1960, 9% averaged 2006-2015



Three different methods have been used to estimate land-use change emissions, indicated here by different shades of grey

Source: [CDIAC]; [Houghton et al 2012]; [Giglio et al 2013]; [Le Quéré et al 2016]; [Global Carbon Budget 2016]

Land Use Change: Forests



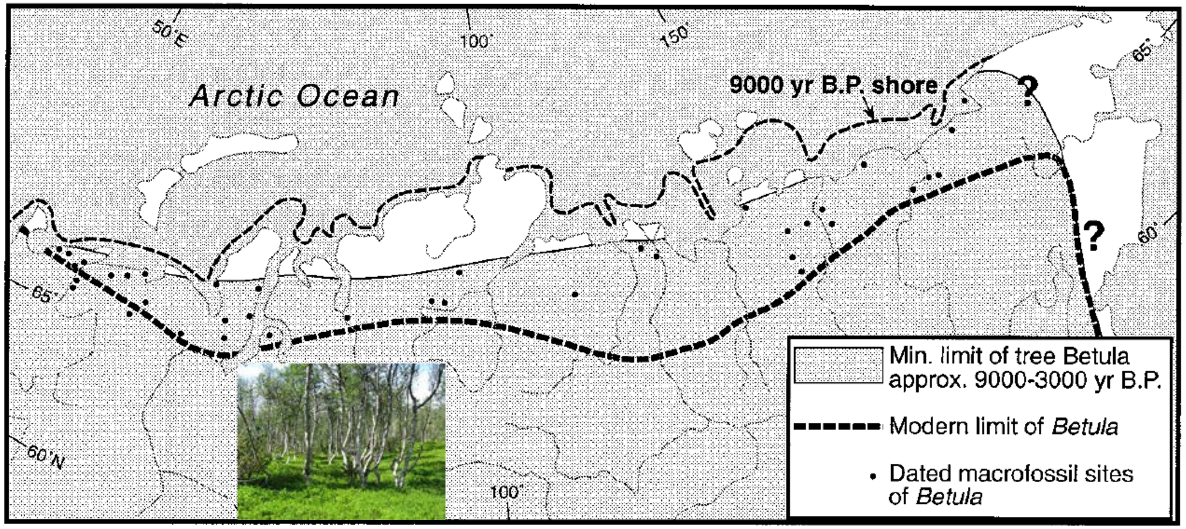
Meyfroidt P, Lambin EF. 2011.
Annu Rev. Environ. Resour. 36:343–71

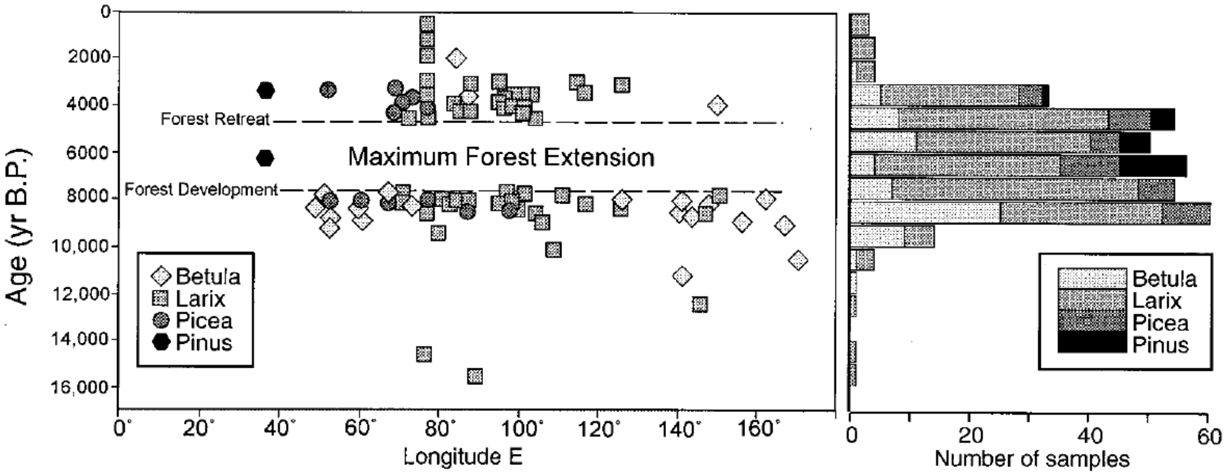
How can we reconstruct land cover and its dynamics?

Dynamics of Northern Forests can be Reconstructed based on Tree Rings

Pine tree with annual growth rings
San Jacinto Wilderness, CA, USA

Reconstruction of the Boreal Tree Line via ^{14}C





Position of low-albedo, C-rich boreal forest affects the Earth's energy budget

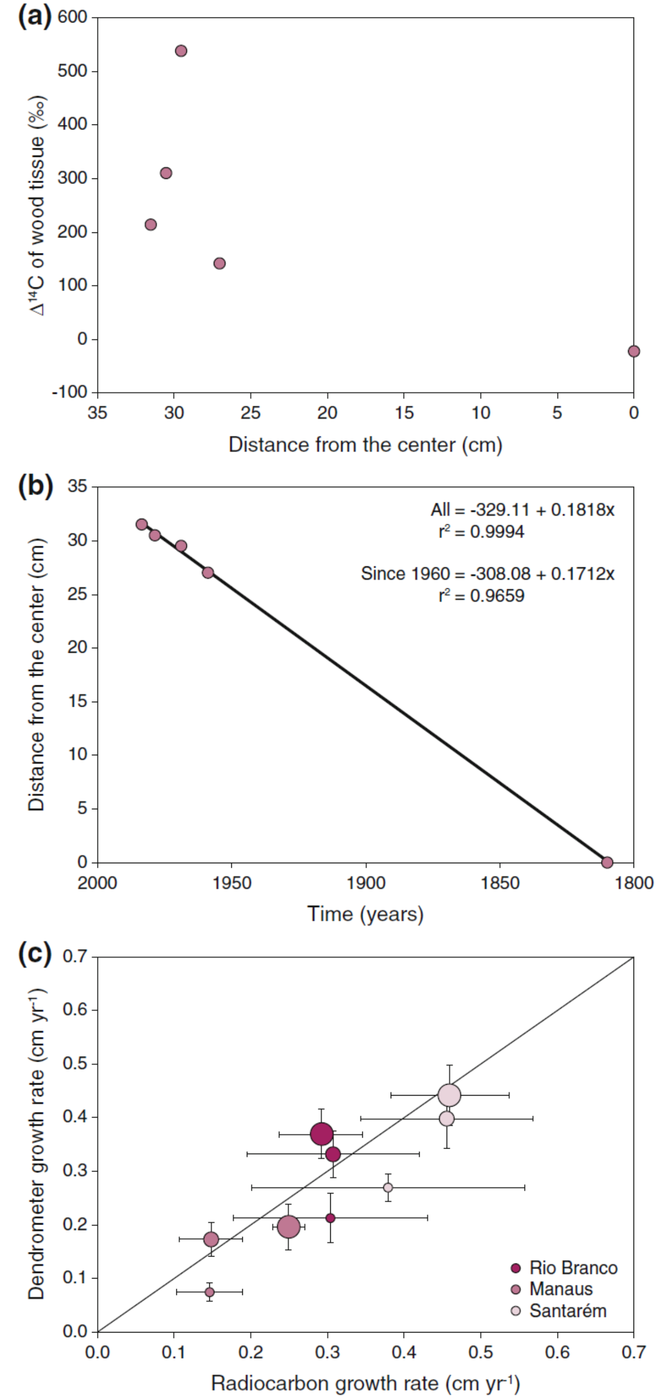
^{14}C-dating of ancient tree stumps reveal:

- Forest advanced to current Arctic coastline between 9-7 kyr B.P.
- Forest retreated to current treeline position by 4-3 kyr B.P.

MacDonald et al. 2000. Quart Res

Dynamics of Tropical Forests can be Reconstructed via ^{14}C

Many tropical trees either lack growth rings or growth rings occur with random (non-annual) periodicity

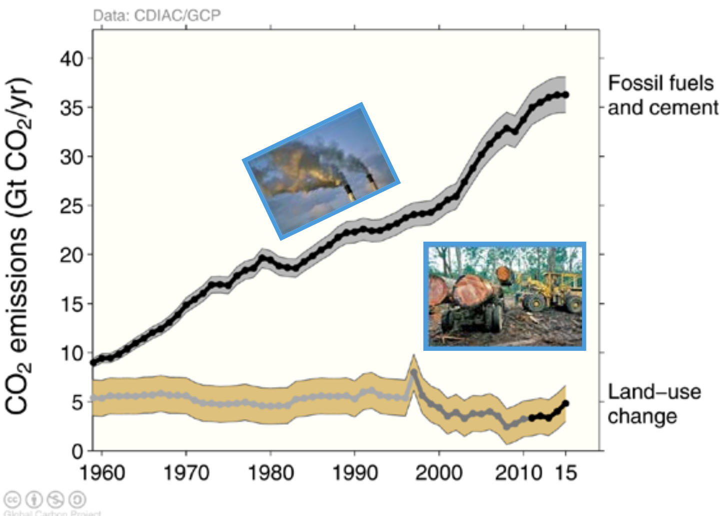


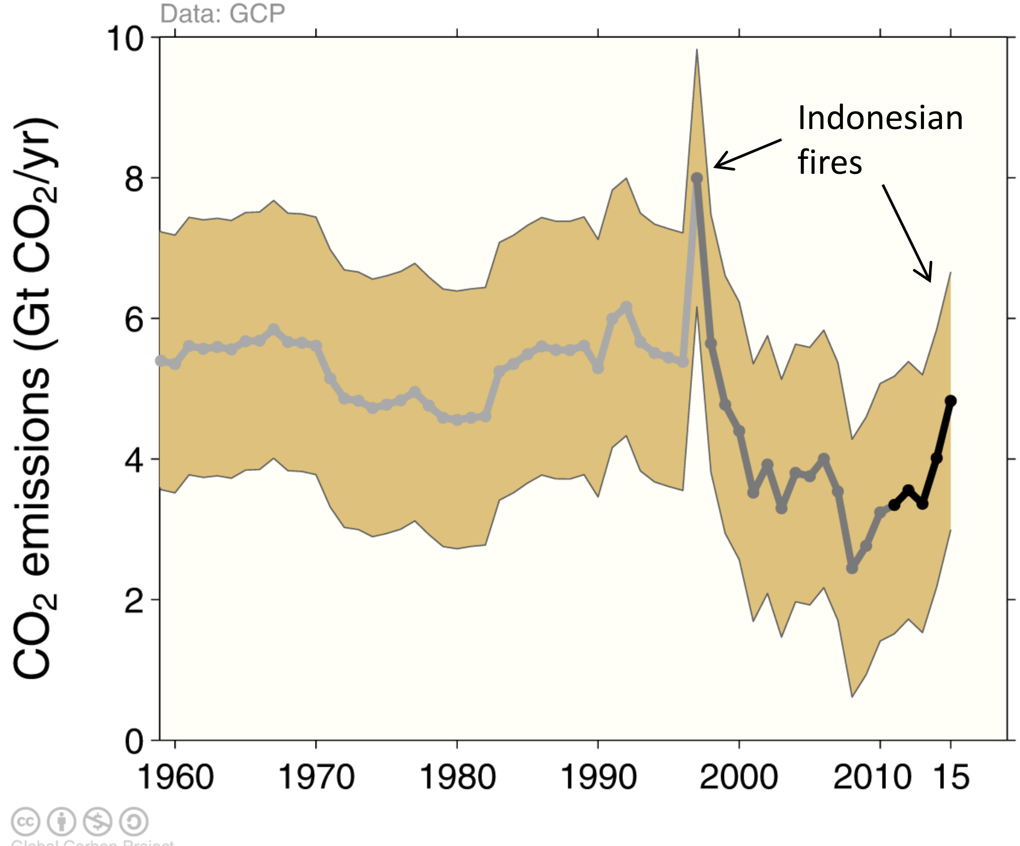
Vieira et al. 2005.PNAS

Total global emissions

Emissions in the 2000s were lower than earlier decades, but highly uncertain

Higher emissions in 2015 are linked to increased fires during dry El Niño conditions in Asia





Three different estimation methods have been used, indicated here by different shades of grey

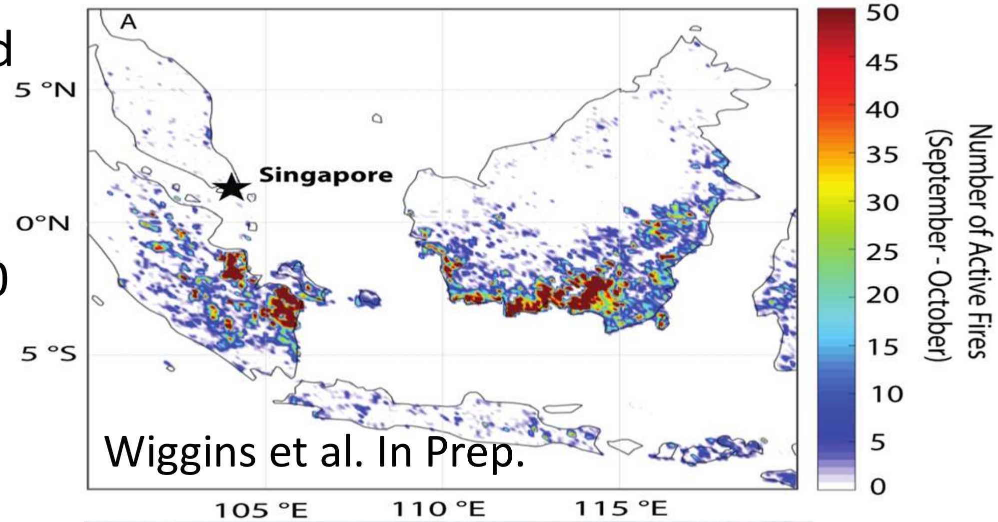
Land-use change also emits CH_4 and N_2O which are not shown here

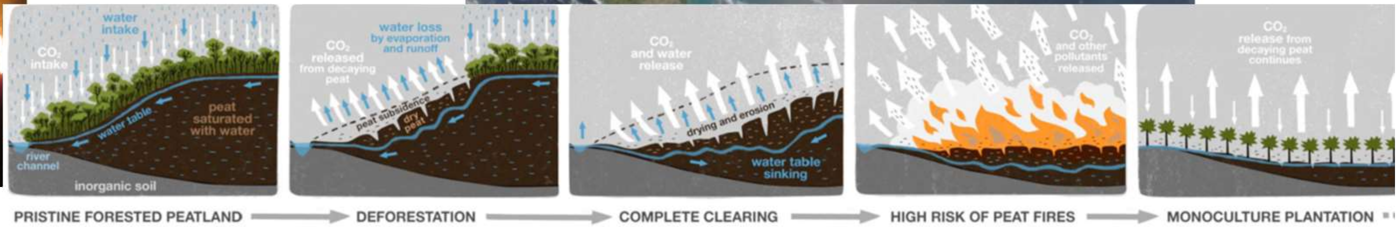
Source: Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

What Burnt during the 2015-2016 El Niño Fires in Indonesia and Malaysia?

Sept. – Oct. 2015: Indonesia experienced exceptionally active fire season exacerbated by El Niño-induced drought

The resulting haze event caused 100,000 premature deaths in Indonesia, Malaysia, and Singapore





Airborne fine particulate matter ($PM_{2.5}$)

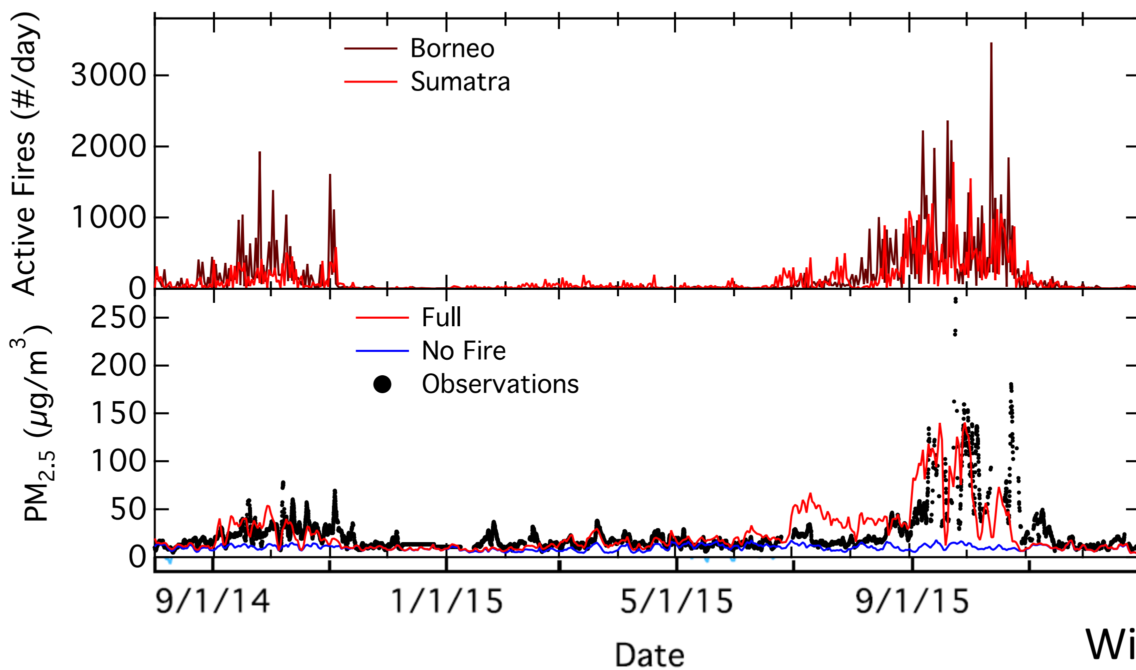
Weekly (7-18 days on 37 mm filters (ADR1500)

Daily on 47 mm (URG)

Collected at the National University of Singapore
1°17′56.65″N, 103°46′16.62″E

2014 fires
(SW monsoon)

2015 fires
(SW monsoon)

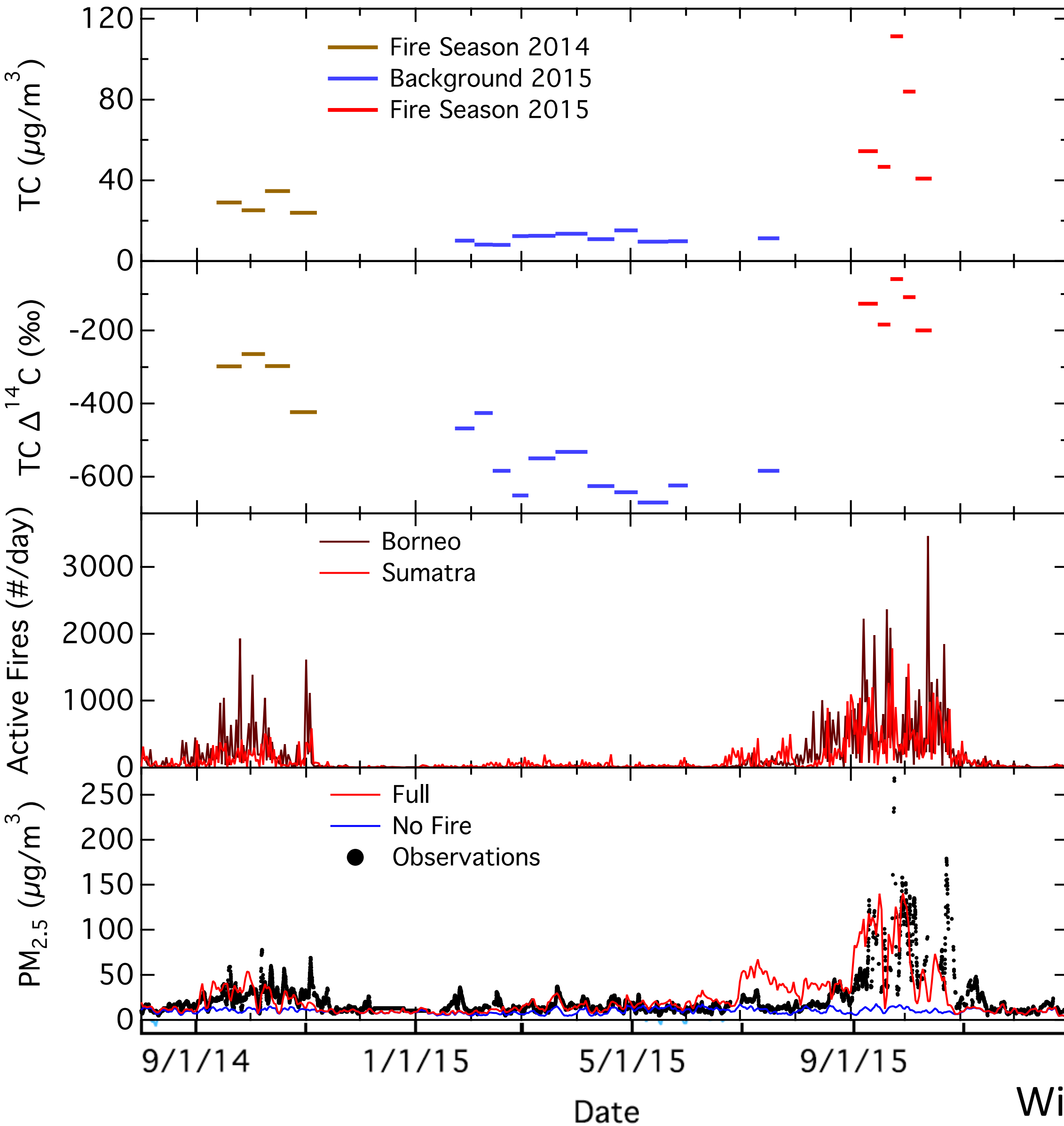


During the fire season, PM2.5 load is higher (enriched in SO_4)

Wiggins et al. In Prep.

2014 fires
(SW monsoon)

2015 fires
(SW monsoon)



During the fire season,

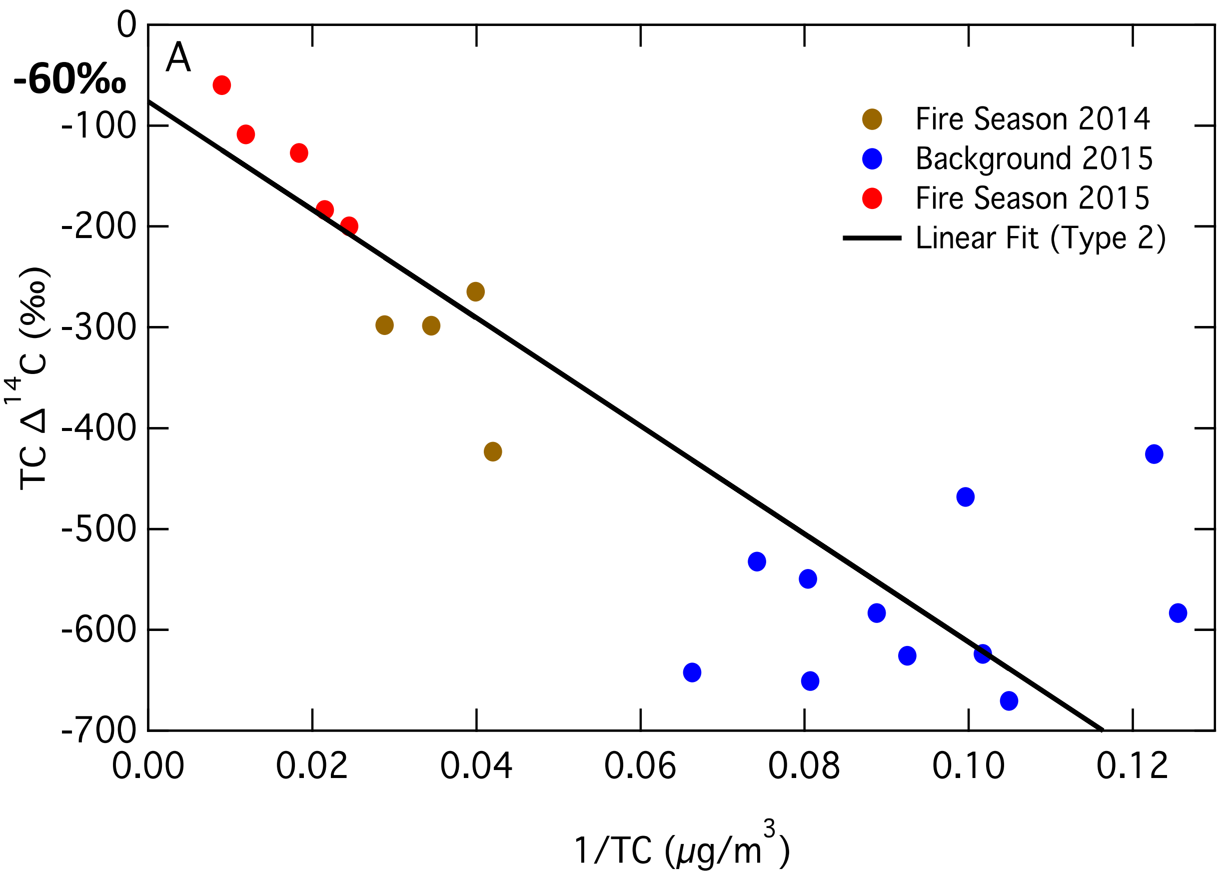
Total C concentrations are higher

Total C is enriched in ^{14}C
(mostly organic C)

PM2.5 load is higher
(enriched in SO_4)

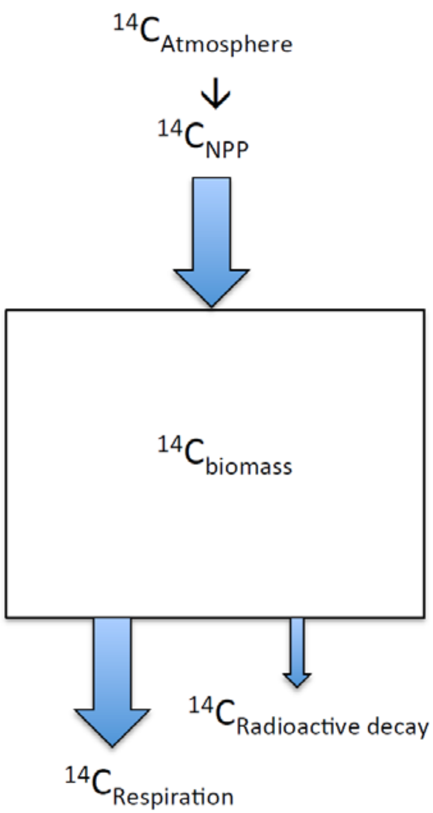
Wiggins et al. In Prep.

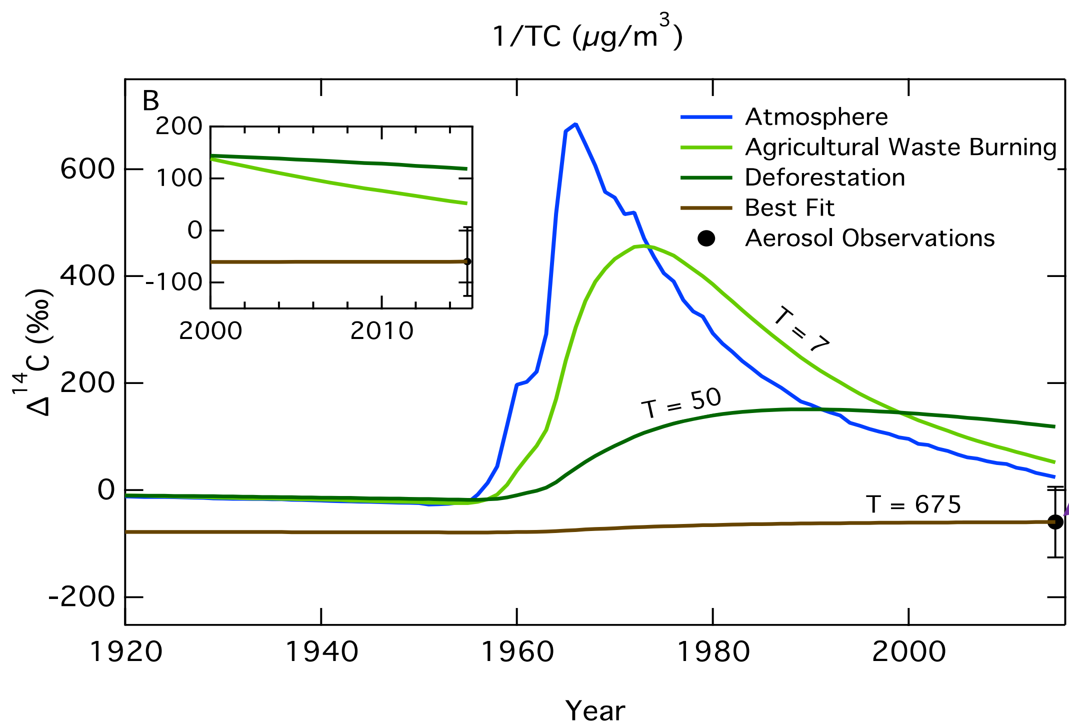
Keeling Plot Reveals Mean Age of Fire Emissions



Wiggins et al. In Prep.

Peat Burning (not crop residue or deforestation) dominated the 2015-2016 El Niño Fires in Indonesia and Malaysia



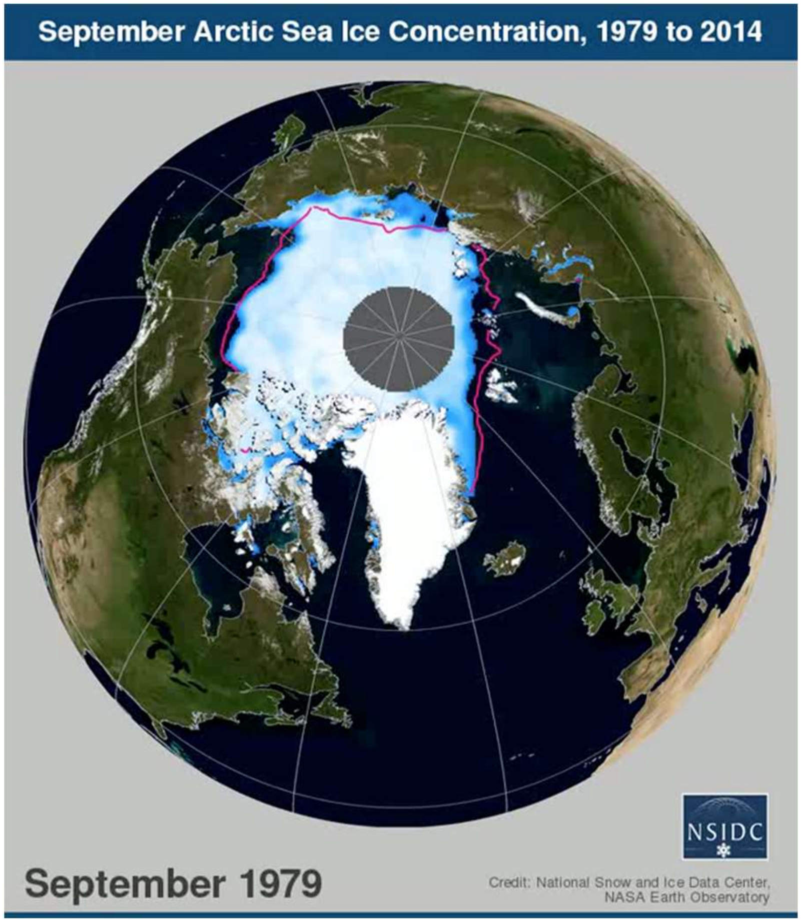


Keeling plot intercept -60‰

Wiggins et al. In Prep.

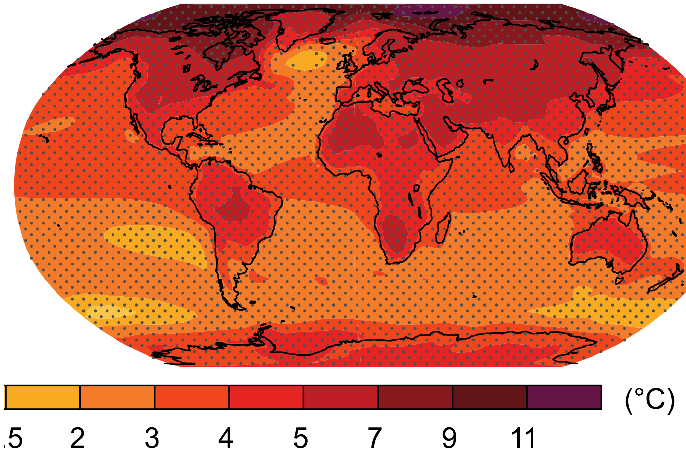
The Arctic is Rapidly Shifting to a New State

Complete loss of summer sea ice by
<2020 (extrapolation of sea ice volume data),
2030 ± 10 yrs (incl. rapid loss events, e.g. 2007),
>2040 (climate model projections)

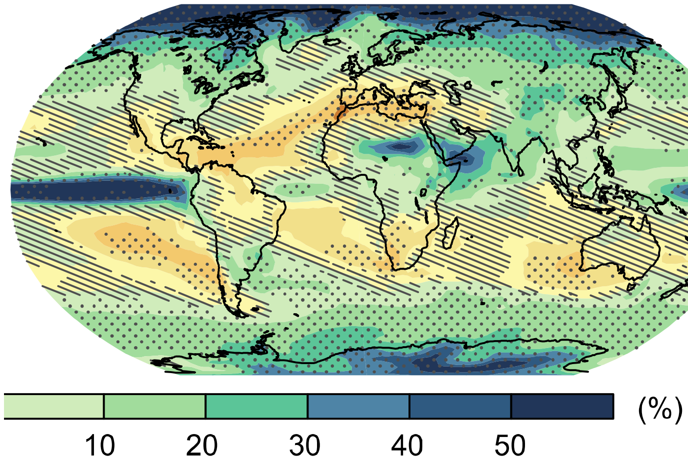


Overland & Wang. 2013. GRL

+6-12ºC MAT by 2100 (*RCP8.5)*



+50% MAP, rain>snow by 2100 (*RCP8.5)*

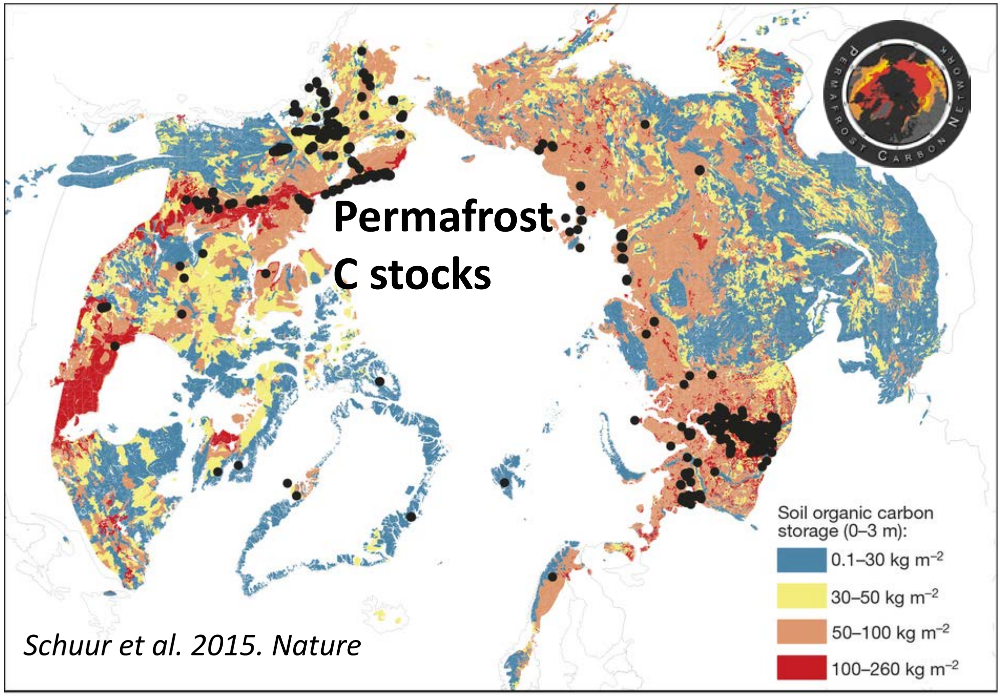


Summary for Policymakers. 2013. IPCC

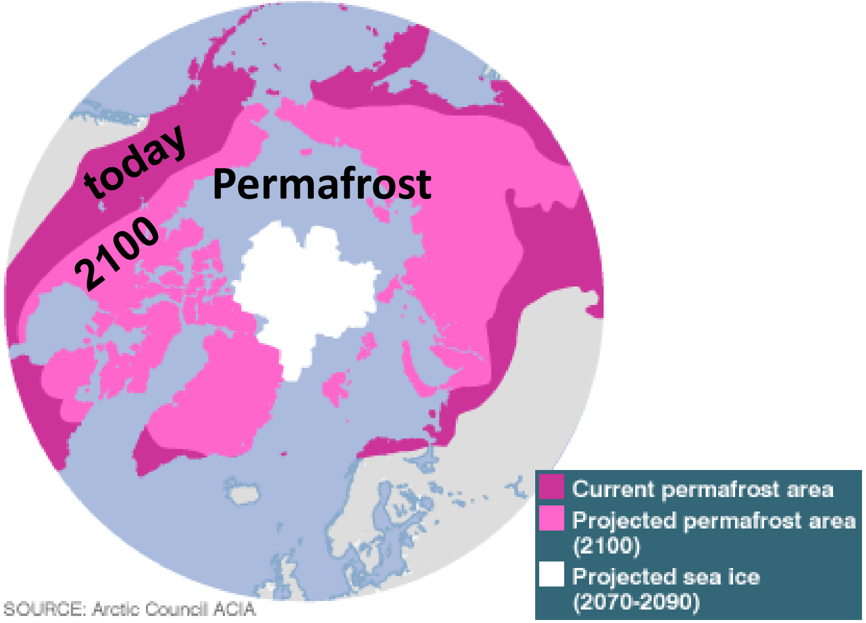
Permafrost Thaw will Expose Vast Soil C Stocks

The northern circumpolar permafrost zone contains vast amounts of C, much of which has been disconnected from the global C cycle for millennia

- 1,035 ± 150 Pg C (0-3 m depth)
- 50% of global soil C
  Rest of the word (excluding Boreal & Arctic): 2,050 Pg C
- ~1-1.5x atmospheric C: 829 Pg C

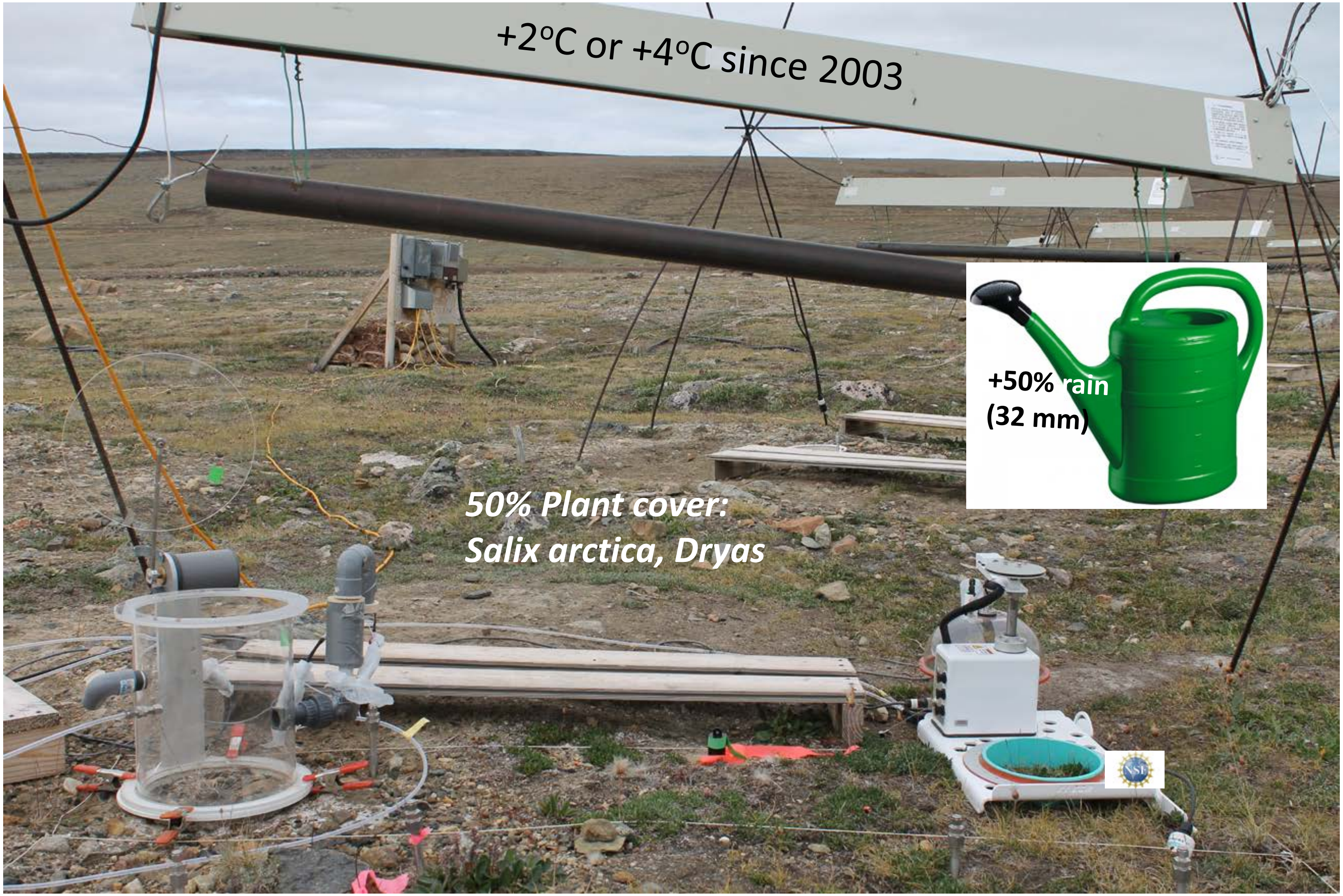


Schuur et al. 2015. Nature

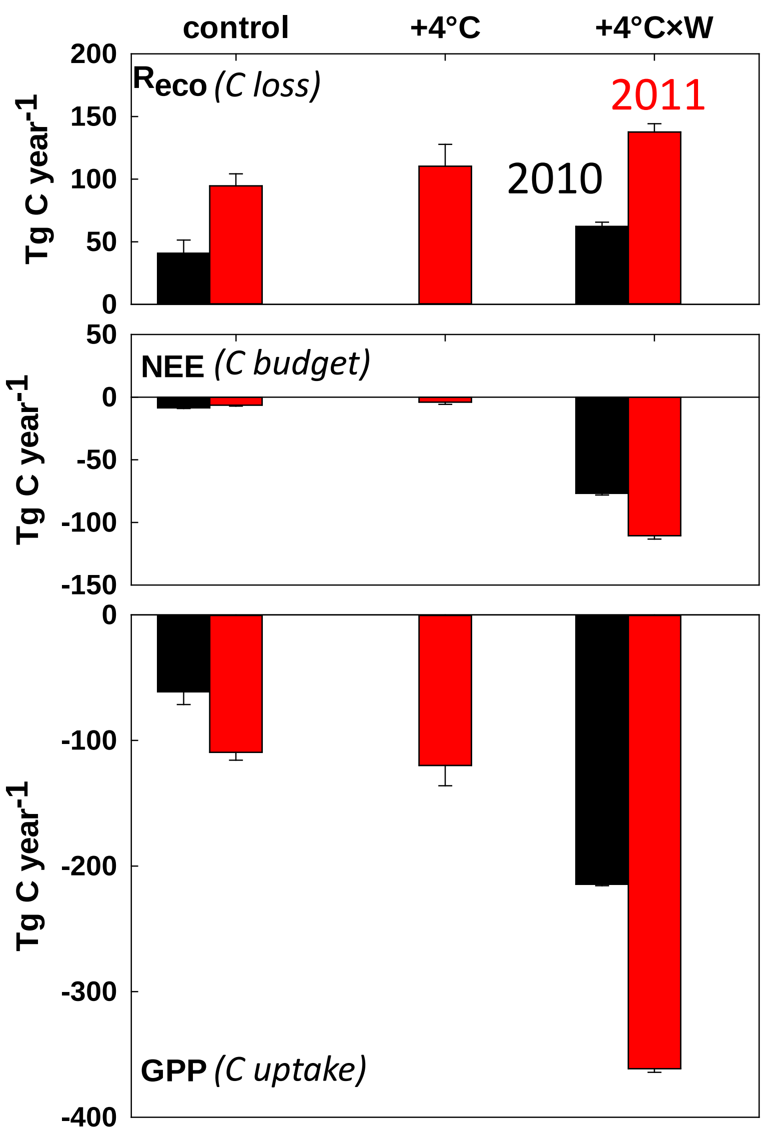


http://news.bbc.co.uk/2/hi/science/nature/4120755.stm

Long-Term Summertime Warming × Wetting of High Arctic Tundra (>70°N)



Climate Change ↑ High Arctic C Sink Strength



Sink Strength (Tg C / summer) High Arctic Semi-Deserts (1 M km^2)	
Current	-6.3±0.8 to -8.5±0.5
Warming-only	-3.9±1.8
Warming × Wetting	-76.8±1.3 to -110.6±2.7

Lupascu et al. 2014. Nature CC

Climate Change ↑ Old C Emissions

Sources of R_{eco} are similar among treatments and mostly modern

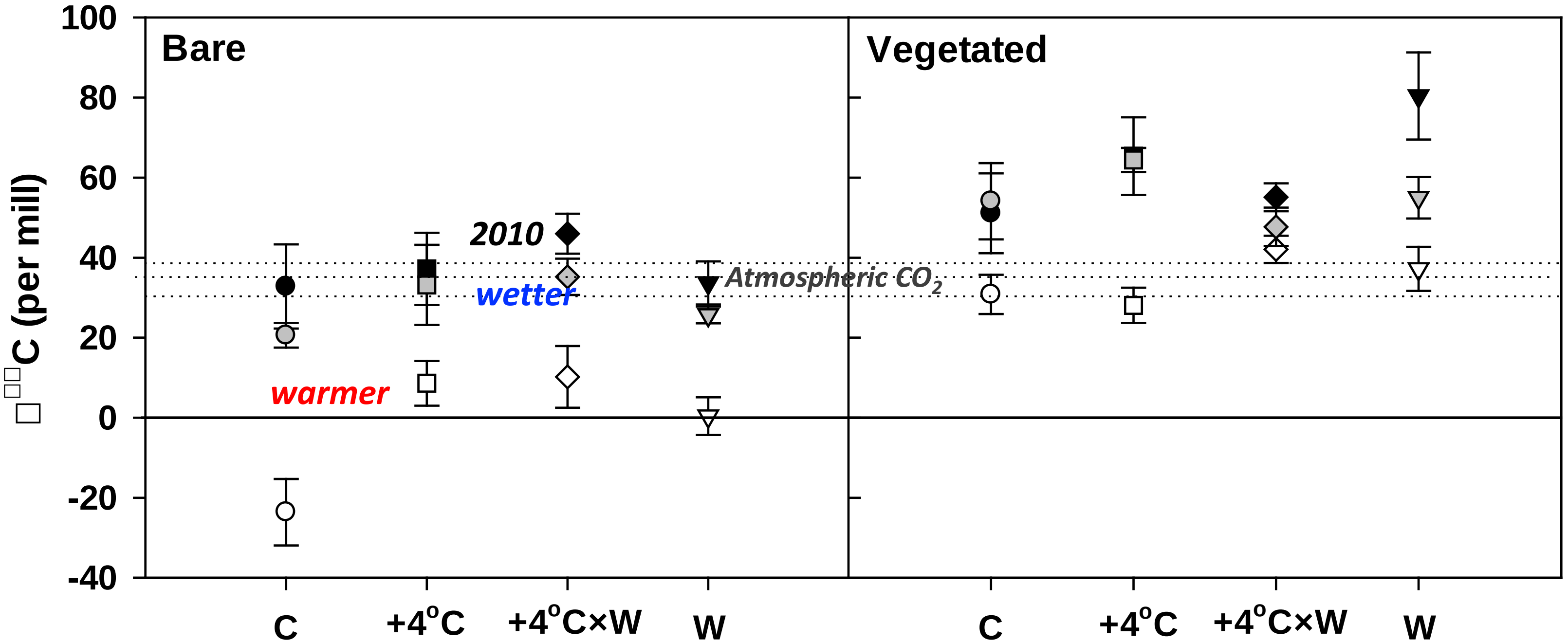
Bare areas emit older C than vegetated areas

R_{eco} is older in warmer summers (deeper thaw)

R_{eco} is younger in wetter summers

Wetting transfers young (surface litter) C to depth where it is decomposed

Deep active layer is wet & cold



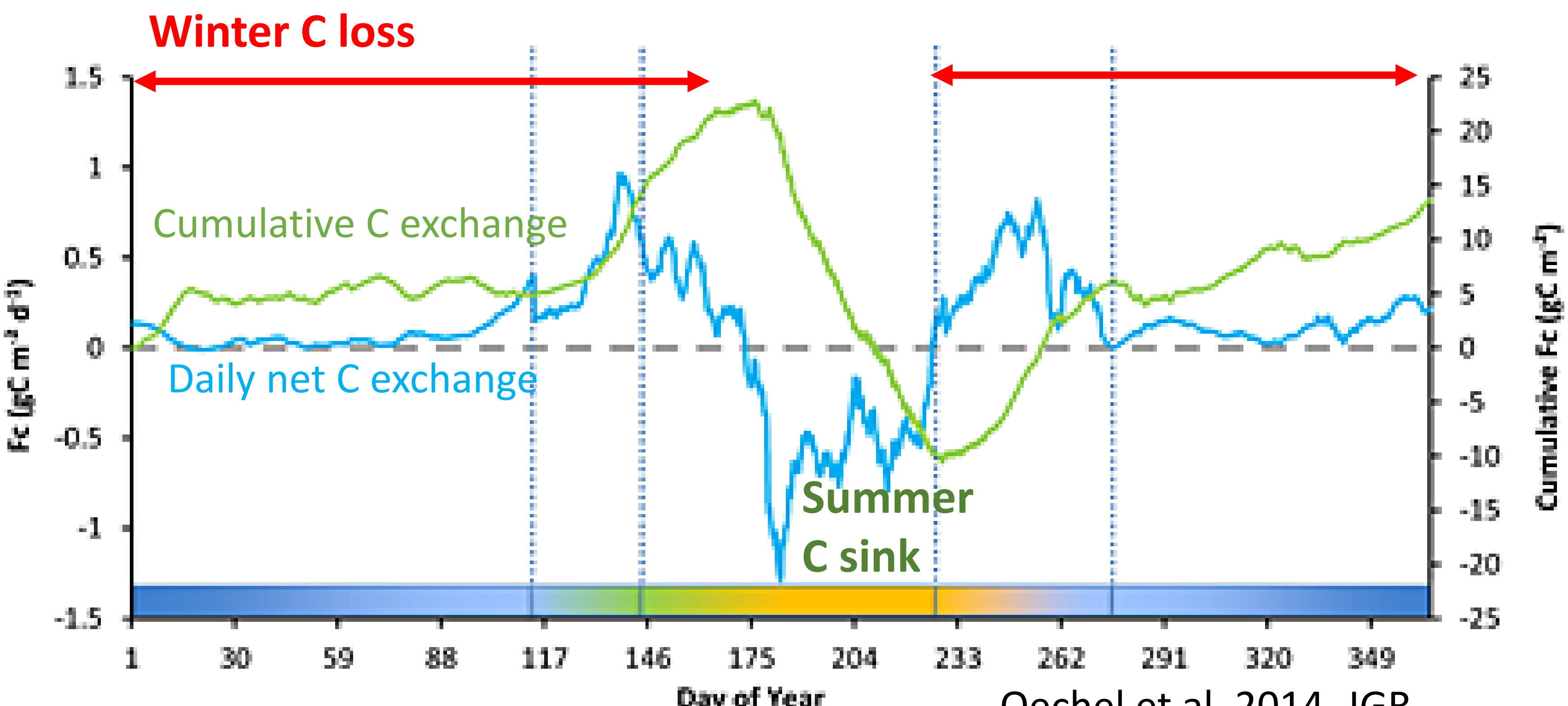
Lupascu et al. 2014. Nature CC; BGS

Polar night, Spitzbergen

Photo by J. Welker

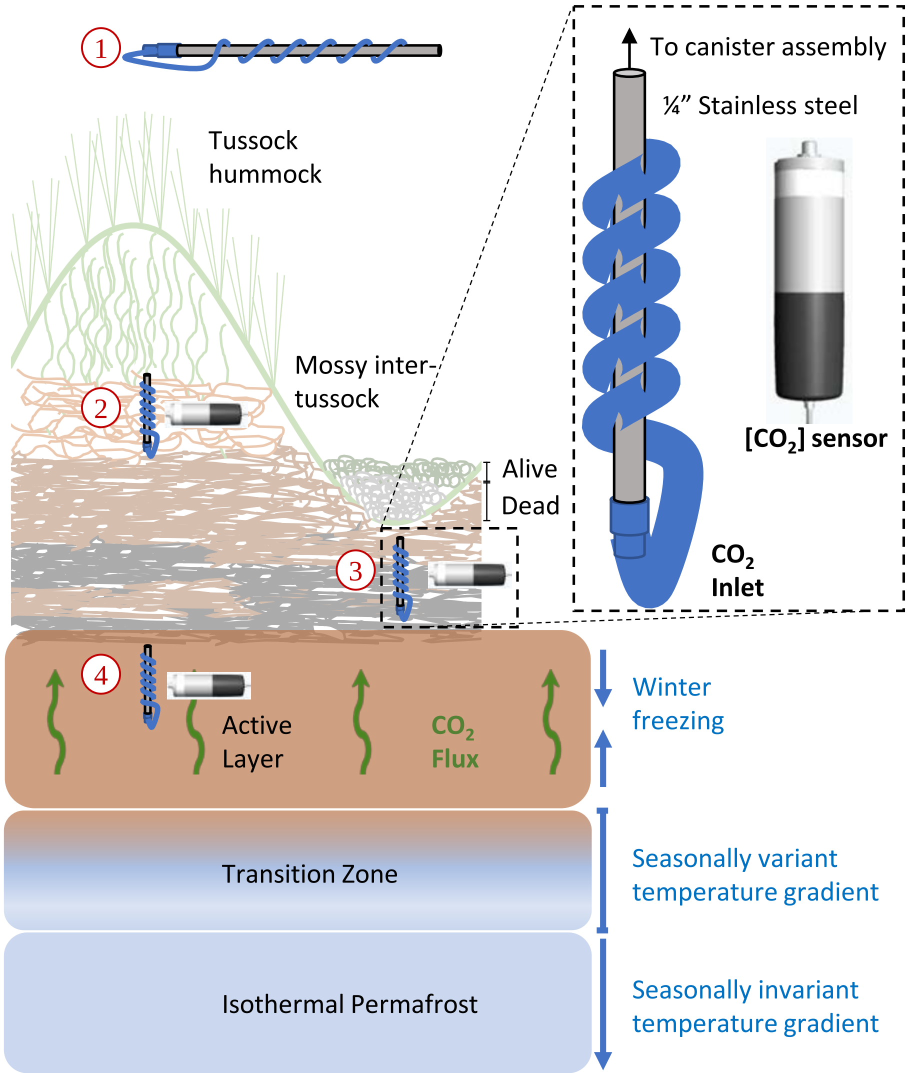
What is the Annual C Budget of different Tundra Ecosystems?

What are non-summer microbial C sources?
Can we monitor permafrost C emissions?



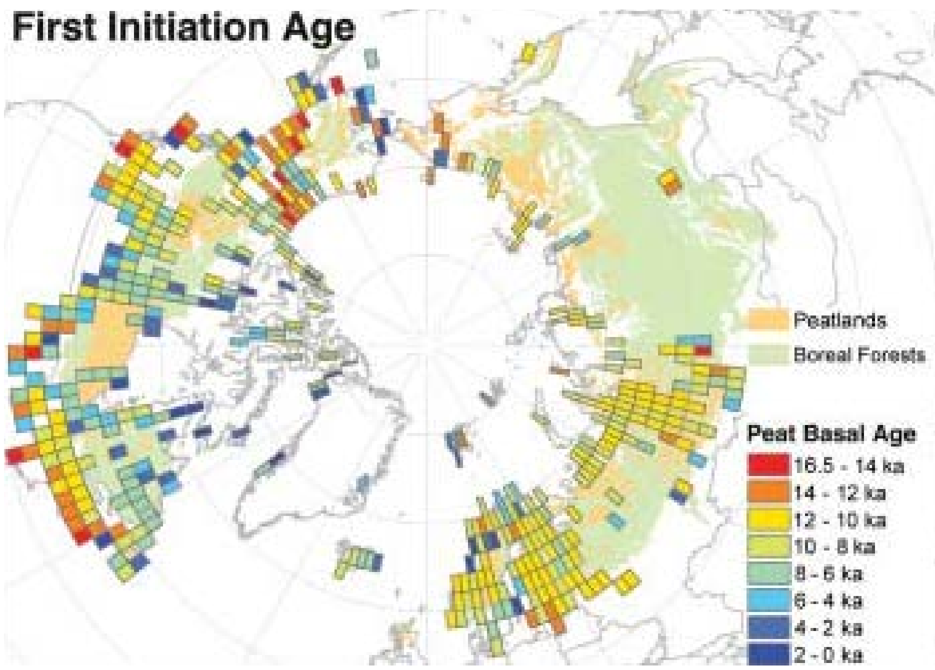
Oechel et al. 2014. JGR

Continuous $^{14}CO_2$ Sampler ©KCCAMS



Pedron et al. In Prep.

Reconstructing Land Cover Change: Initiation of Northern Peatlands



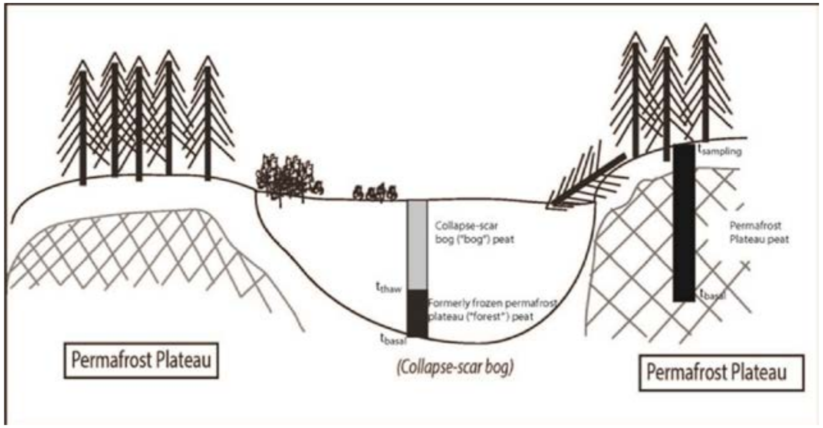
Modern northern peatlands cover 4 M km^2 across Eurasia and North America and store 180-455 Pg C, while also releasing 20-45 Tg CH_4 yr^{-1}

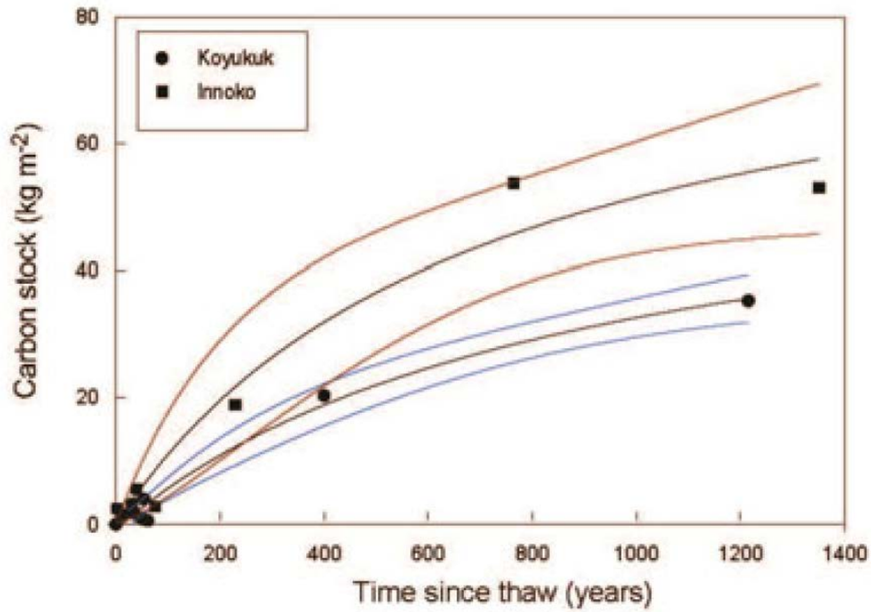
^{14}C-dating basal peat (bulk & macrofossils) shows:

- No extensive peatland complex before 16.5 ka
- Rapid expansion between 12 and 8 ka
- Fens → bogs

MacDonald et al. 2006. Science

Rapid C Loss and Slow Recovery following Permafrost Thaw in Boreal Peatlands?

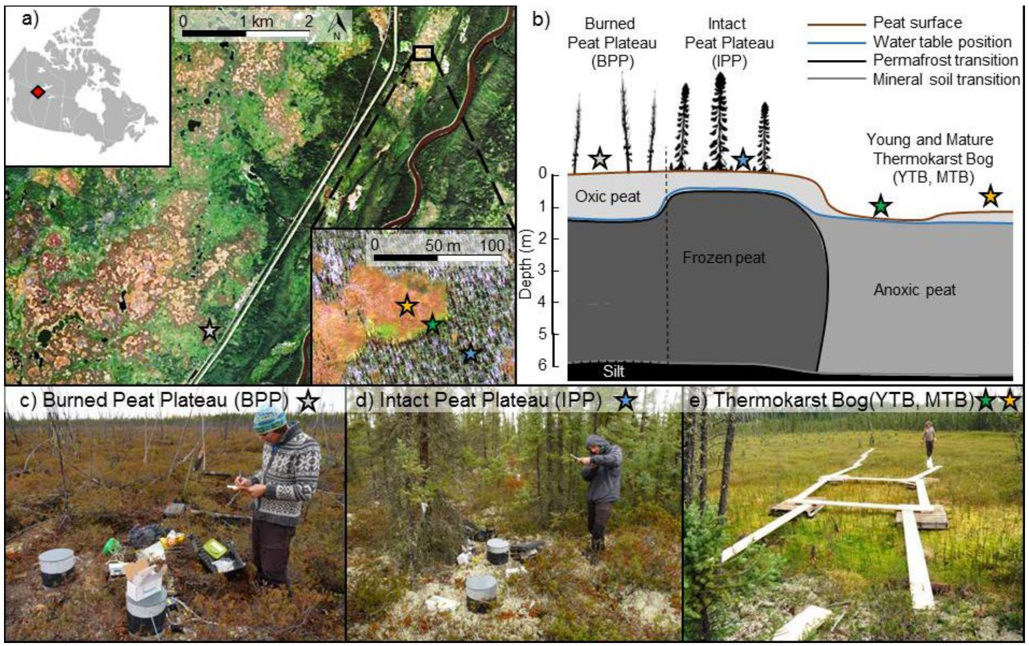


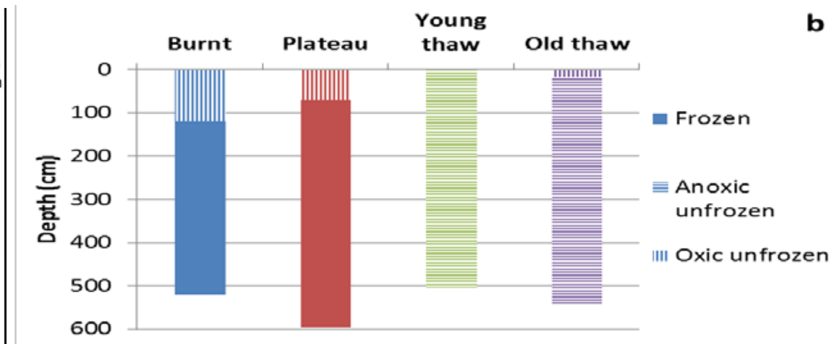


Upon thaw, C loss of the forest peat C is equivalent to ~30% of the initial forest C stock, and is directly proportional to the pre-thaw C stocks. Recover is slow (centuries to millennia)

Jones et al. 2016 GCB

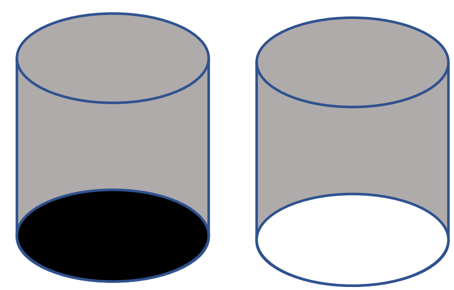
Rapid C Loss and Slow Recovery following Permafrost Thaw in Boreal Peatlands?



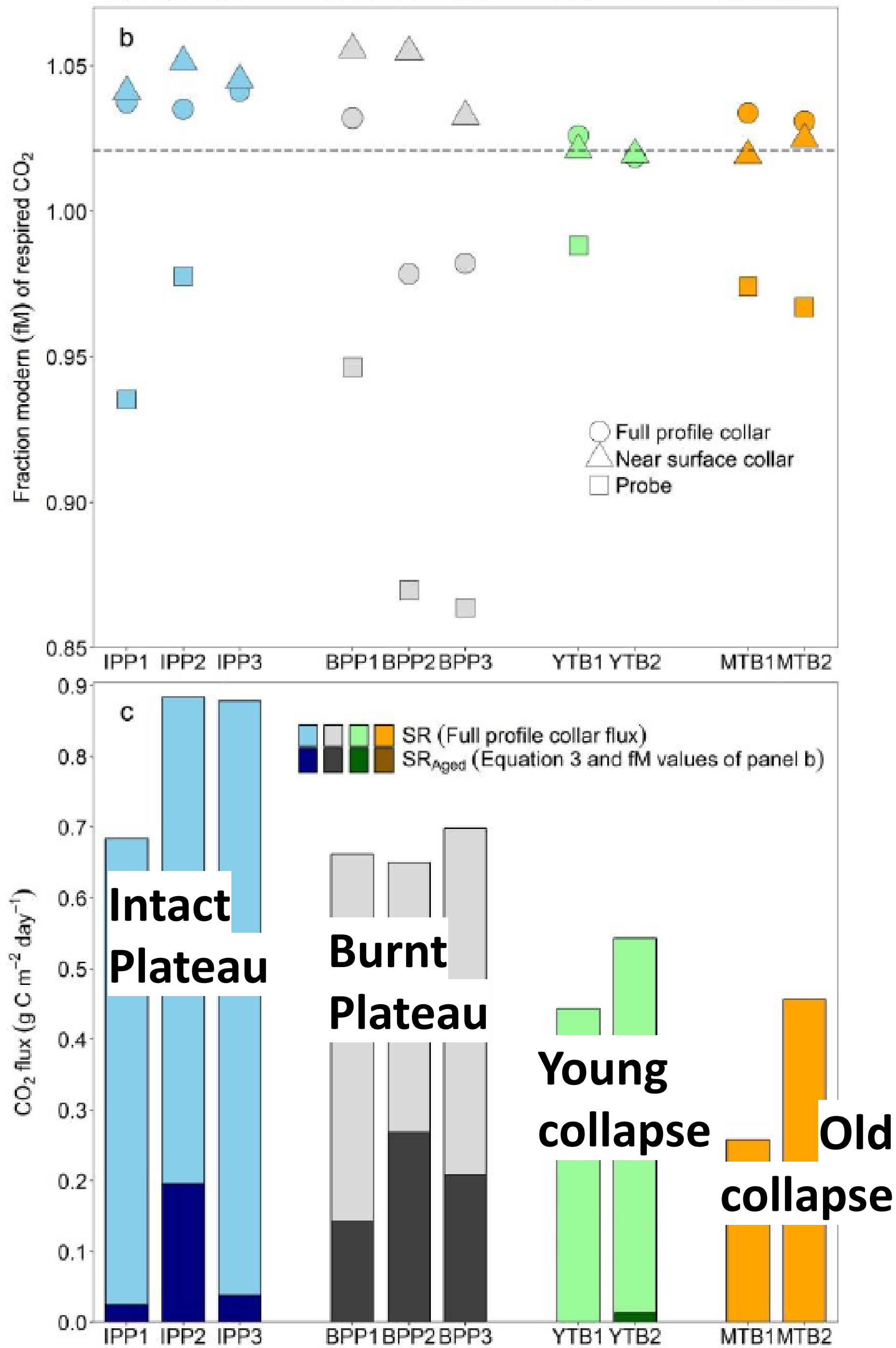


Surface soil only

Total profile



Estop-Aragones et al. In Review
Radiocarbon Short Course 2016



Warming (active layer deepening) of peat plateaus with oxic soils → 5x increase in respiration of aged soil C (1,600 yrs BP),
>20% of total respiration

Thaw & collapse →
no contribution from aged soil C to respiration, rapid C accrual

Interactions between wildfire and dominant mode of permafrost thaw will strongly influence the future stability of aged soil C in northern peatlands

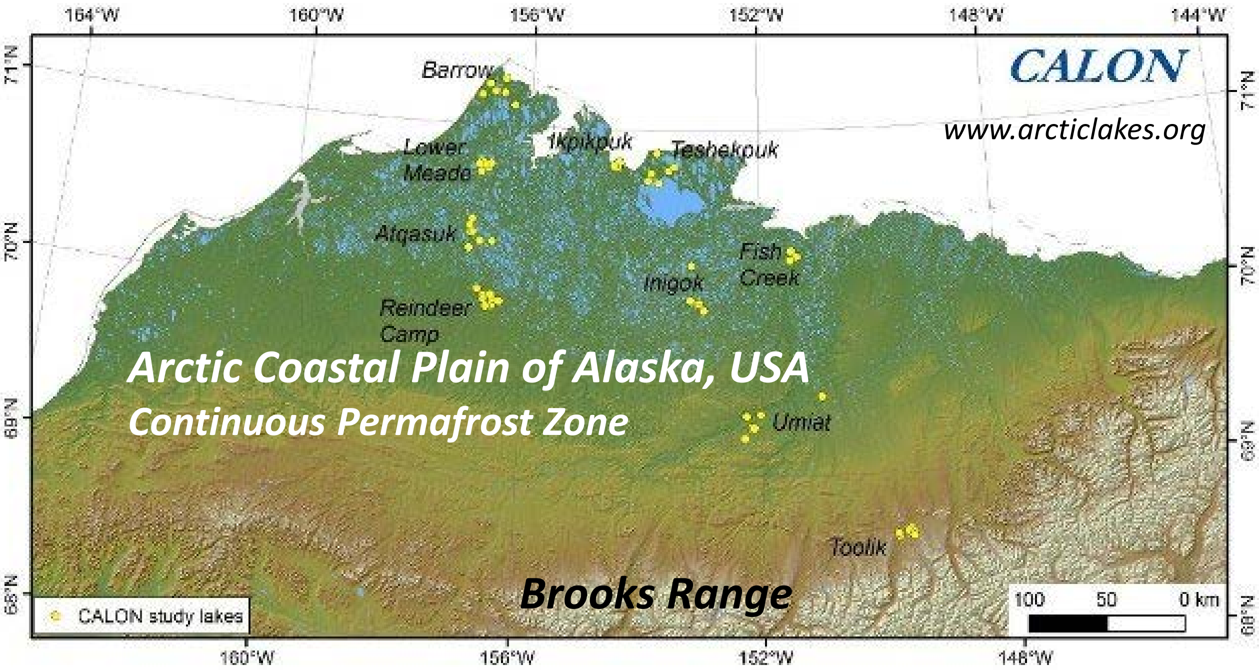
Estop-Aragones et al. In Review

Thaw Lakes: Shortcuts to Permafrost C?

K. Walter Anthony, University of Alaska, Fairbanks

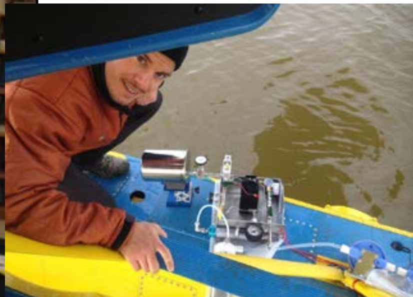
- Northern lakes (>50ºN) represent one of the largest natural CH_4 sources: 16.5 Tg CH_4 yr^{-1}
- On a per lake basis, CH_4 emission rates are greatest from shallow thermokarst lakes on yedoma
- Ebullition accounts for up to 79% of the total ice-free season flux, but is highly sporadic in space and time
  - Average: 140.6 mg CH_4 m^{-2} d^{-1}
  - IQR: 77–188
  - Maximum: 461 mg CH_4 m^{-2} d^{-1}
- Ebullition CH_4 is sourced from highly variable carbon sources
  - Mean ^{14}C-age varies from 40,000 years BP to modern

Thaw lakes on the AK's North Slope



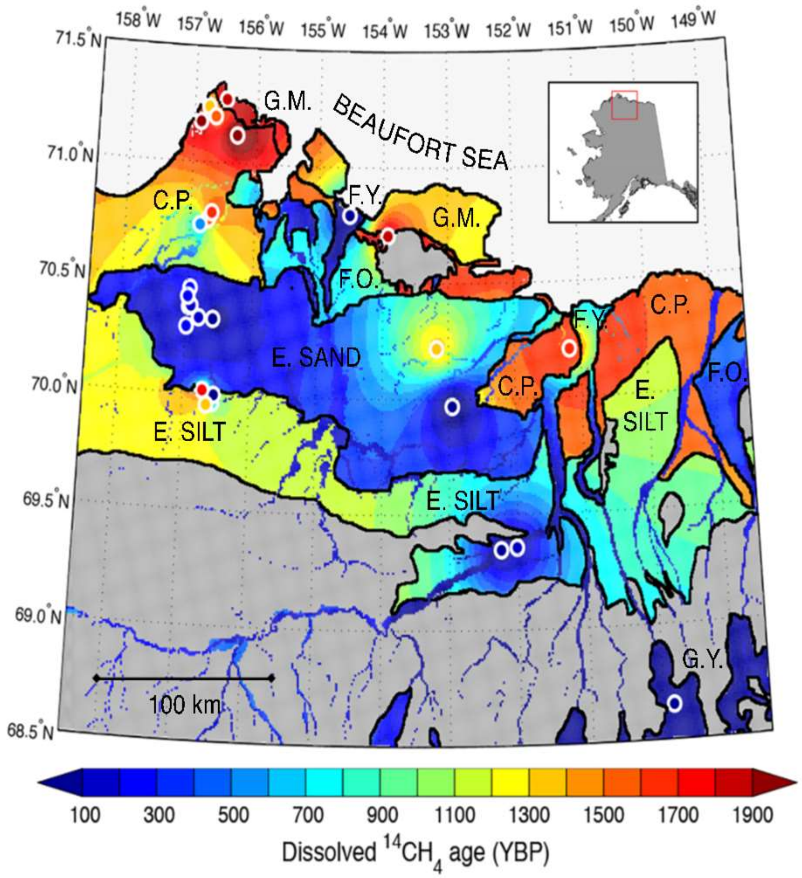
We studied the ^{14}C-age and magnitude of C emissions from 40 thaw lakes with floating ice regime

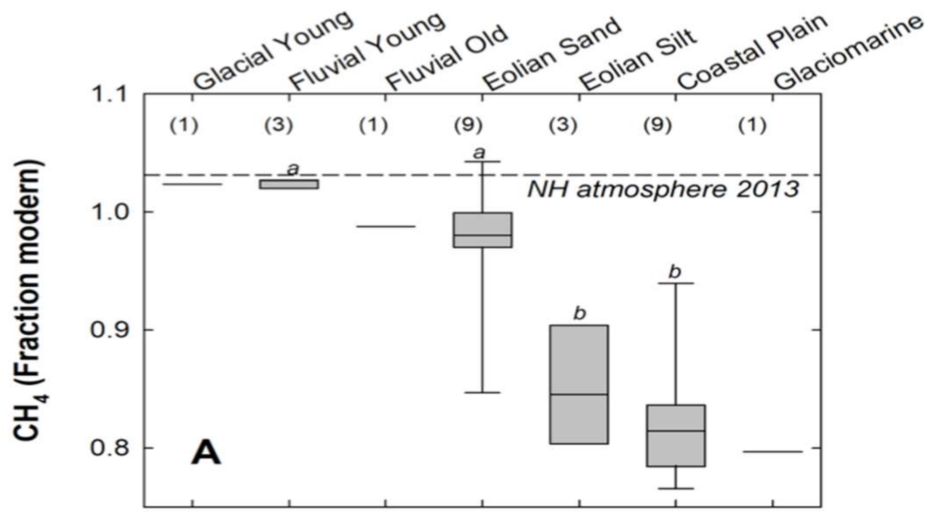
2 N-S transects spanning 7 geology types, incl. yedoma-type eolian silt, eolian sand & glaciomarine deposits



Elder et al. In Review

Today, North Slope Thaw Lakes Emit Young C as CO_2





Thaw lakes emit 0.89 ± 0.02 Tg C (diffusive C-CO_2 + C-CH_4) yr^{-1}) (99% CO_2)

C emissions are young:
CH_4 modern to 3,300 ± 70 years BP
CO_2 modern to 1,590 ± 20 years BP

Older emissions are restricted to finer-textured deposits

Elder et al. In Review

Land ^{14}C-opportunities

	Days	Months to Years	Years to Decades	Centuries to Millennia
Techniques	Pulse-labeling ^{13}C & ^{14}C Natural Abundance ^{13}C	Pulse-labeling ^{14}C Continuous labeling ^{13}C & ^{14}C Natural Abundance ^{13}C	Bomb ^{14}C Incorporation Suess effect	Natural abundance ^{14}C
C pools	Plant metabolism & associated microbes, NSCs	Plant metabolism NSCs Storage New Growth Decomposition	NSCs Storage Growth SOM Dynamics Decomposition	Growth SOM Dynamics Decomposition Land cover