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Increased atmospheric CO_2 and the transit time of carbon in terrestrial ecosystems

Global Change Biology, *29*(23), 6441–6452.

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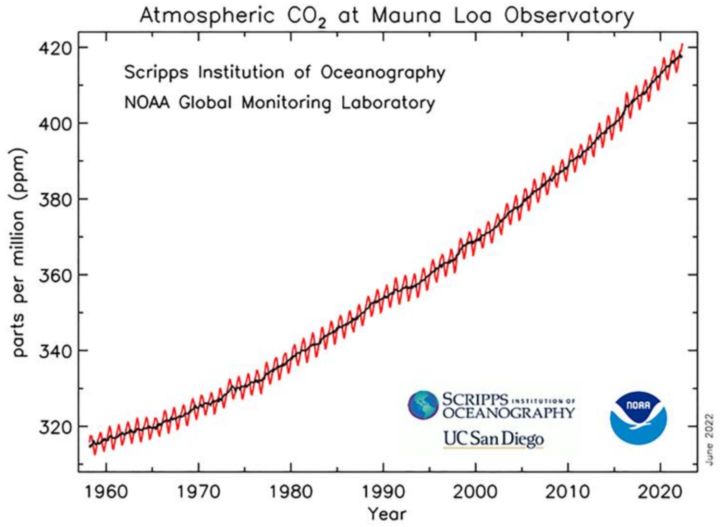
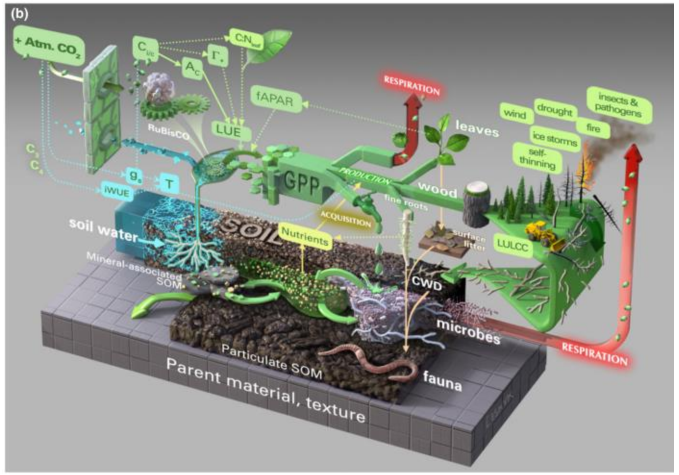
What happens to the fixed carbon by the vegetation?

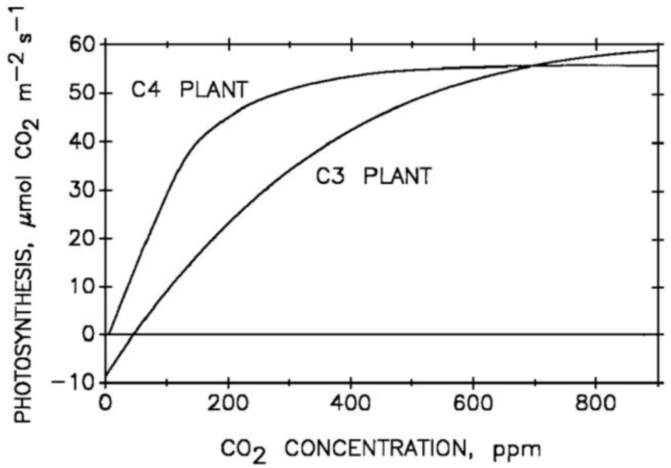


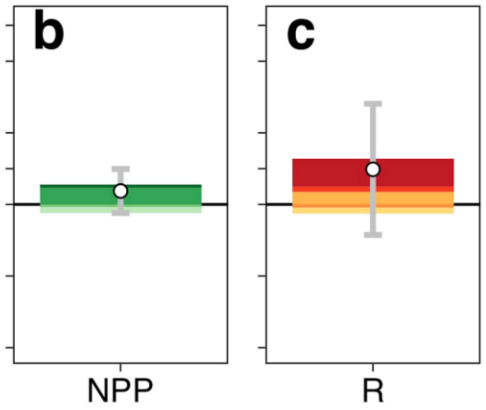


- Where is it allocated?
- How long it remains stored?
- How do changes in abiotic factors modify ecosystem metabolism?

Walker et al. (2021). *New Phytologist*, *229*(5), 2413–2445.

What happens to extra carbon fixed by vegetation?





Vegetation is fertilized under increased CO_2 turning **assimilated carbon into biomass.**

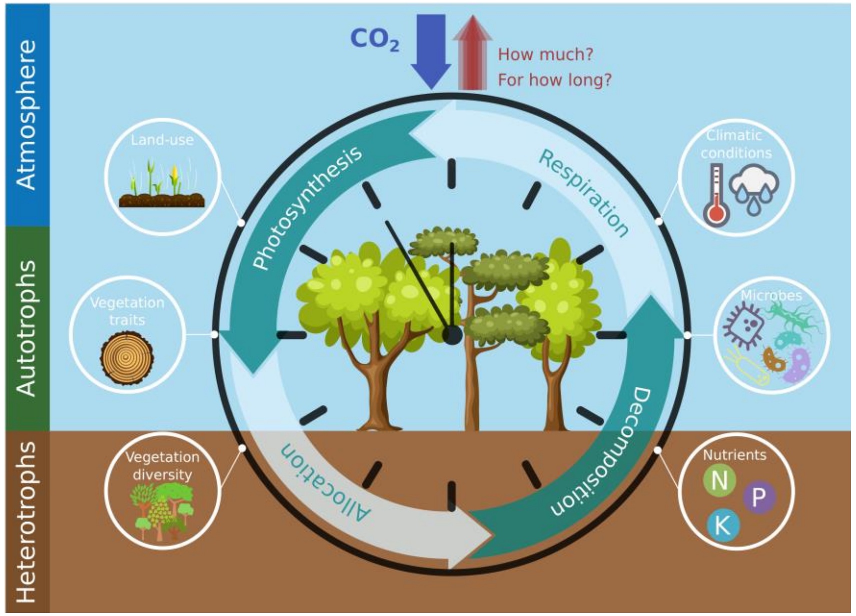
Extra assimilated **carbon is emitted back to the atmosphere** via respiratory fluxes.

Allen & Goodman (2004). Encyclopedia of plant and crop science, 346-348.
Jiang et al. (2020). *Nature*, *580*(7802), 227–231.

Comprehensive quantification of iCO_2 effects involves answering how much and for how long carbon is stored

Many authors have asked the challenging question **¿where does the carbon go?**

e.g. De Kauwe et al., 2014; Jiang et al., 2020; Körner et al., 2007.

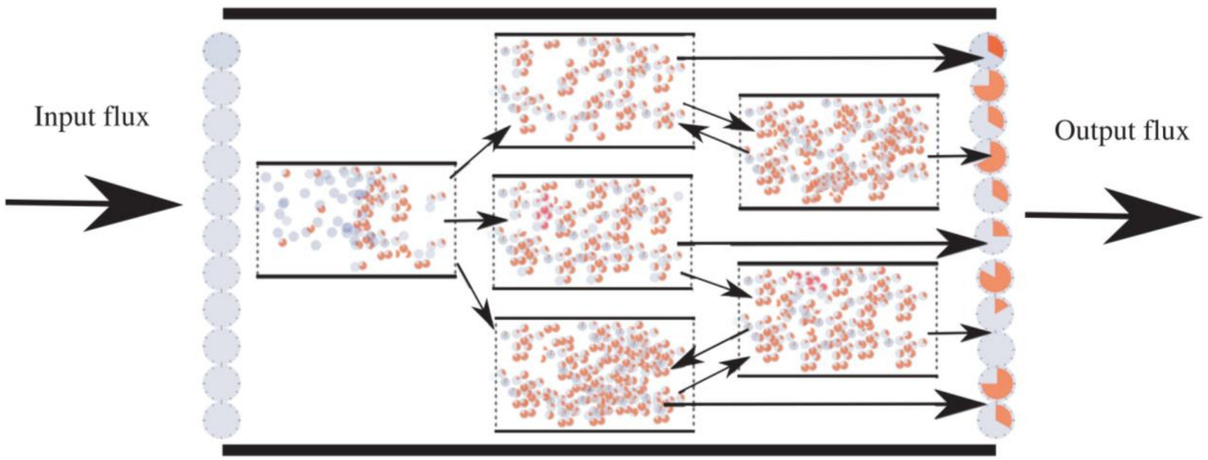


Continuous range of temporal scales:

- **Hours to days**: assimilation and respiration of simple photosynthates.
- **Centuries to millennia:** organic matter transfers to soil.

How much and **for how long** is carbon stored in an ecosystem?

Key concept: transit time distribution of carbon



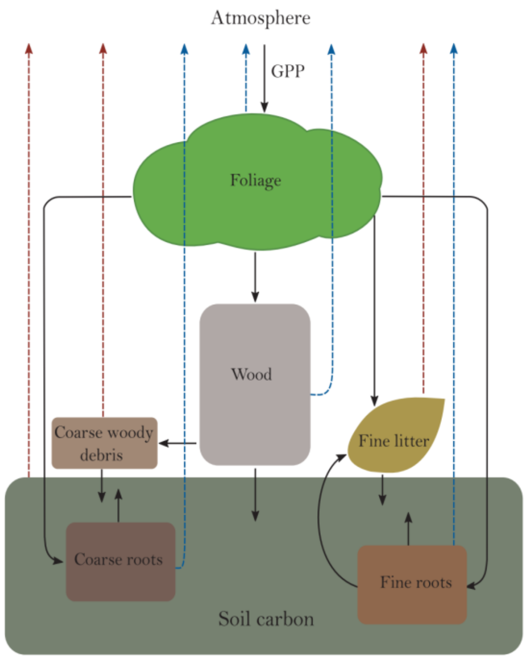
Transit time (τ): time elapsed since carbon enters the system until it is released.

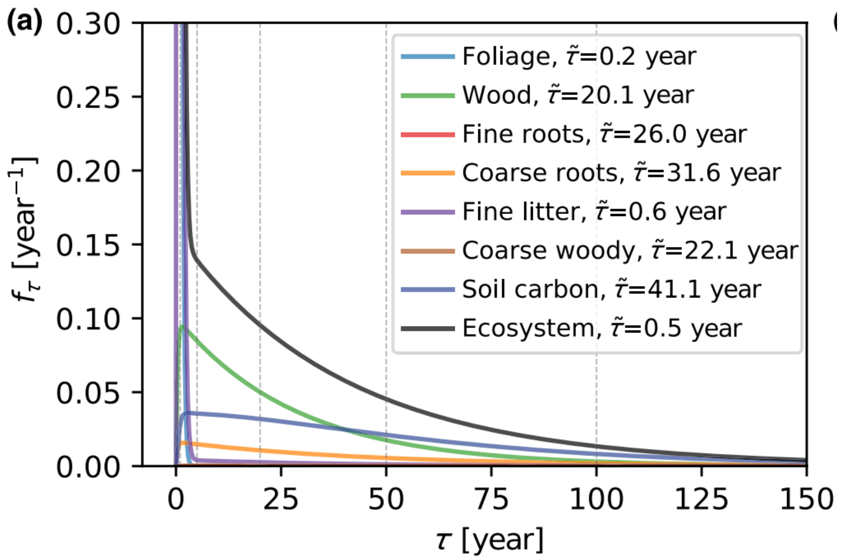
- Linking of main ecosystem processes
- Covering a wide range of temporal scales
- Field experiments and modelling.

Sierra et al. (2017). *Global Change Biology* 23 (5), 1763-1773.

τ describes how C fixed returns to the atmosphere over a wide range of temporal scales

$$\dot{\mathbf{x}}(t) = \boldsymbol{u} + \mathbf{B}\mathbf{x}(t)$$

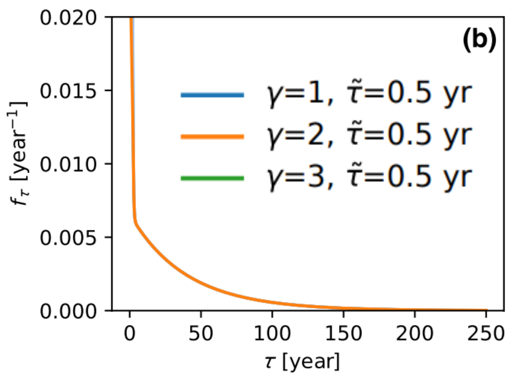




- Most carbon from **foliage** and **fine litter** is respired in very **short timescales**.
- At **longer timescales**, almost all carbon is being respired except some proportions from the **soil** and the **roots**.
- The dynamics of the **ecosystem** are driven by what happens in each pool **differently over time**.

Sierra, C. et al. (2021). *Journal of Ecology* 109(8), 2845-2855.

The time carbon spends in ecosystems is the same regardless of how much carbon enters



$$\dot{\mathbf{x}}(t) = \gamma \mathbf{u} + \mathbf{B}\mathbf{x}(t)$$

u=carbon inputs from atmosphere

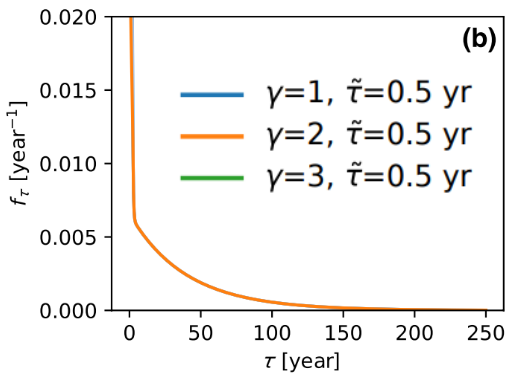
$$\mathbb{E}(\tau) = -\mathbf{1}^\intercal \mathbf{B}^{-1} \frac{\gamma \mathbf{u}}{\| \gamma \mathbf{u} \|}$$

The behavior of one unit of assimilated carbon is the same.

The time carbon spends in ecosystems depends on carbon fate and the rates at which it is processed

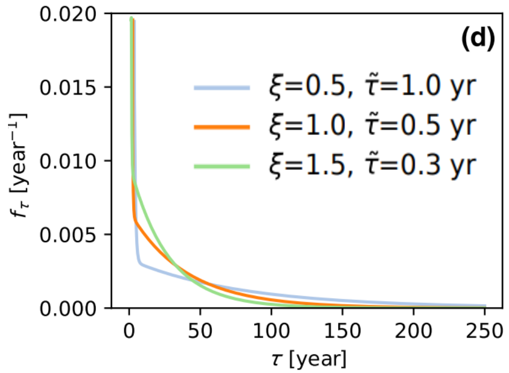
$$\dot{\mathbf{x}}(t) = \gamma \mathbf{u} + \xi \mathbf{B}\mathbf{x}(t)$$

B=carbon cycling and transfer rates



$$\mathbb{E}(\tau) = -\mathbf{1}^{\intercal}\mathbf{B}^{-1}\frac{\gamma\mathbf{u}}{\|\gamma\mathbf{u}\|}$$

The behavior of one unit of assimilated carbon is the same.



$$\frac{\mathbb{E}(\tau)}{\xi} = -\mathbf{1}^{\intercal}(\xi\mathbf{B})^{-1}\frac{\mathbf{u}}{\|\mathbf{u}\|}$$

The behavior of one unit of assimilated carbon changes.

There are three techniques for obtaining the carbon transit time

- **Modelling:** Mass balance equations
- **Induced tracers:** isotopic labelling techniques
- **Natural tracer:** $\Delta^{14}C$

These methods are complementary: tracers provide independent measurement-based information useful for model structure identification, parameterization and calibration.

Concluding remarks and implications

1. τ distribution provides **key** information to understand the **effect of iCO_2** in terrestrial ecosystems.

2. τ permits the study of **future scenarios** of fossil fuel emissions and potential interaction with other factors such as **nutrient** and **water availability**.

3. In mature forests, most carbon fixed does not remain stored for long timescales. If iCO_2 leads to **increased biomass** and carbon accumulation, important **changes in B** must be responsible.

Thanks!

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For further discussion:
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MARIE SKŁODOWSKA-CURIE ACTIONS

τ quantifies the proportions of extra carbon stored in biomass and respired back

Generalized nonlinear nonautonomous → **Linear autonomous**

$$\frac{d\mathbf{x}}{dt} = \dot{\mathbf{x}}(t) = \boldsymbol{u}(\mathbf{x}(t), t) + \mathbf{B}(\mathbf{x}(t), t) \cdot \boldsymbol{x}(t)$$

x: content of carbon
u: external carbon inputs
B: rates of carbon cycling and transfers.

$$\dot{\mathbf{x}}(t) = \boldsymbol{u} + \mathbf{B}\mathbf{x}(t)$$

$$f(\tau) = -\mathbf{1}^{\mathsf{T}}\ \mathbf{B}\ \mathrm{e}^{\tau\mathbf{B}}\ \frac{\boldsymbol{u}}{\|\boldsymbol{u}\|}$$

$$\mathbb{E}(\tau) = -\mathbf{1}^{\mathsf{T}}\mathbf{B}^{-1}\frac{\mathbf{u}}{\|\mathbf{u}\|}$$

τ Captures different **paths** that a particle of C could take to travel through an ecosystem and **how much time** it would be stored.

Proportion of new extra carbon:
- Stored in biomass
- Respired back

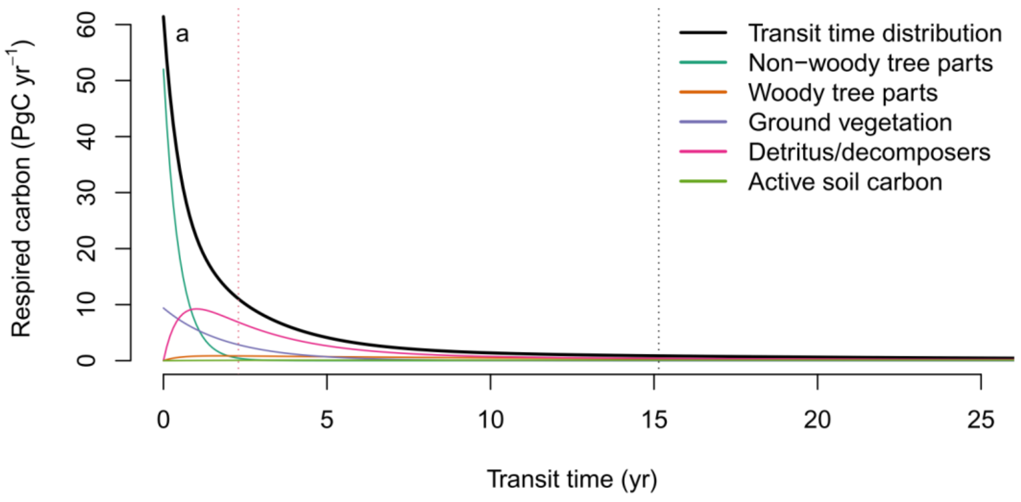
τ quantifies the proportions of extra carbon stored in biomass and respired back

Linear autonomous

$$\dot{x}(t) = u + Bx(t)$$

$$f(\tau) = -\mathbf{1}^\intercal \ B \ e^{\tau B} \ \frac{u}{\| u \|}$$

$$\mathbb{E}(\tau) = -\mathbf{1}^\intercal B^{-1} \frac{u}{\| u \|}$$



Sierra, C., et al. "A decrease in the age of respired carbon from the terrestrial biosphere and increase in the asymmetry of its distribution." *PTRS A* 381.2261 (2023).

τ Captures different **paths** that a particle of C could take to travel through an ecosystem and **how much time** it would be stored.

Proportion of new extra carbon:
- Stored in biomass
- Respired back

Key concept: transit time distribution of carbon

Objective: **Usefulness and robustness** of transit time concept (Bolin & Rodhe, 1973; Eriksson, 1971; Thompson & Randerson, 1999) for understanding the **effects of iCO_2** on ecosystem carbon dynamics.

- What transit time is?
- Example of usefulness
- Currently available techniques for quantification
- Final remarks