Grand Challenges in Carbon Cycle Modelling

Big questions

- How will climate affect greenhouse gas sources and sinks in the biosphere and with what impact on the climate system?
- How can we improve long-term projections of the global carbon system, including effects through natural ecosystems and changing anthropogenic emissions?
- How do the carbon, water and energy cycles interact and how does this affect climate? Does this change with with time scale?
- How will changing climate and direct human impacts affect the biosphere and the services it provides to humanity?

Our notion of a fresh start isn't new Sellers and Schimel… at a similar moment…

Sellers P, Schimel D. Remote sensing of the land biosphere and biogeochemistry in the EOS era: Science priorities, methods and implementation—EOS land biosphere and biogeochemical cycles panels. Global and Planetary Change. 1993 Jun 1;7(4):279-97.

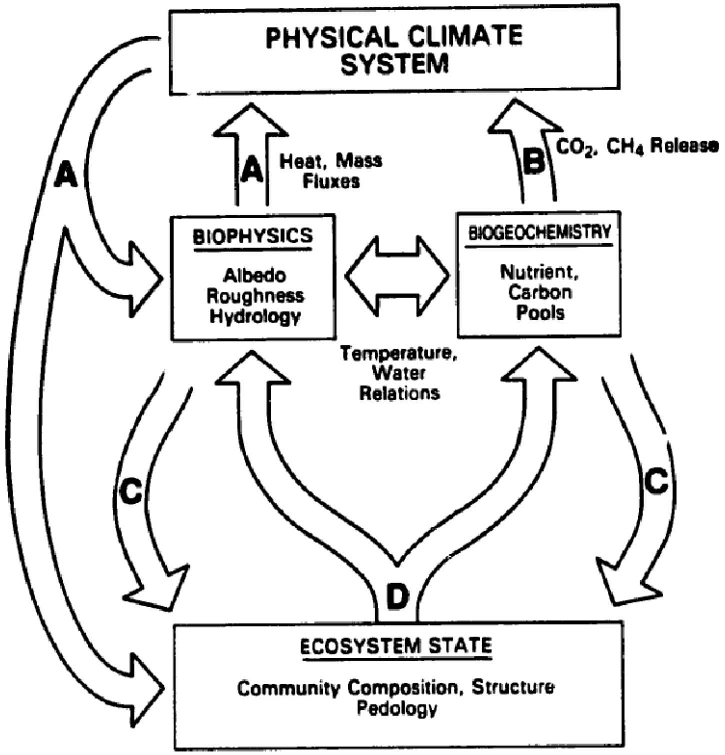


Fig. 1. Important interactions between the vegetated land surface and the atmosphere with respect to global change. (A) Influence of changes in the Physical Climate System on biophysical processes. These may feedback onto the atmosphere through changes in energy, heat, water and CO_2 exchange. (B) Changes in nutrient cycling rates; release of CO_2 and CH_4 from the soil carbon pool back to the atmosphere. (C) Changes in biogeochemical processes and water and nutrient availability influence community composition and structure. (D) Change in species composition results in changes in surface biophysical characteristics and biogeochemical process rates.

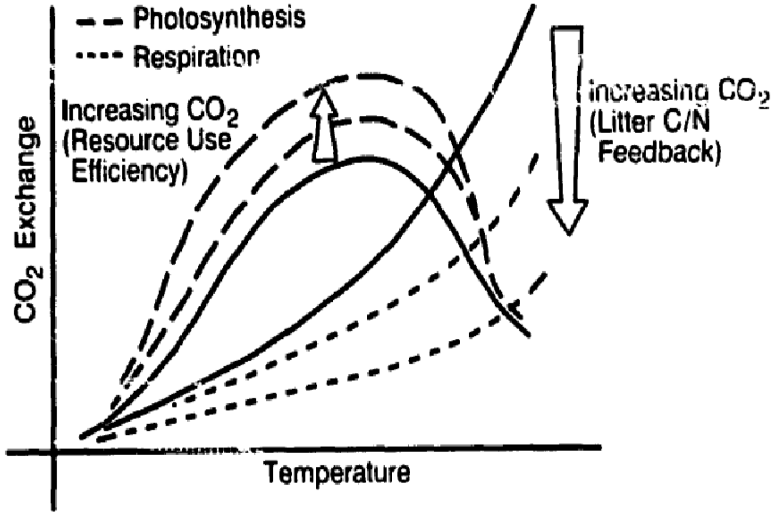
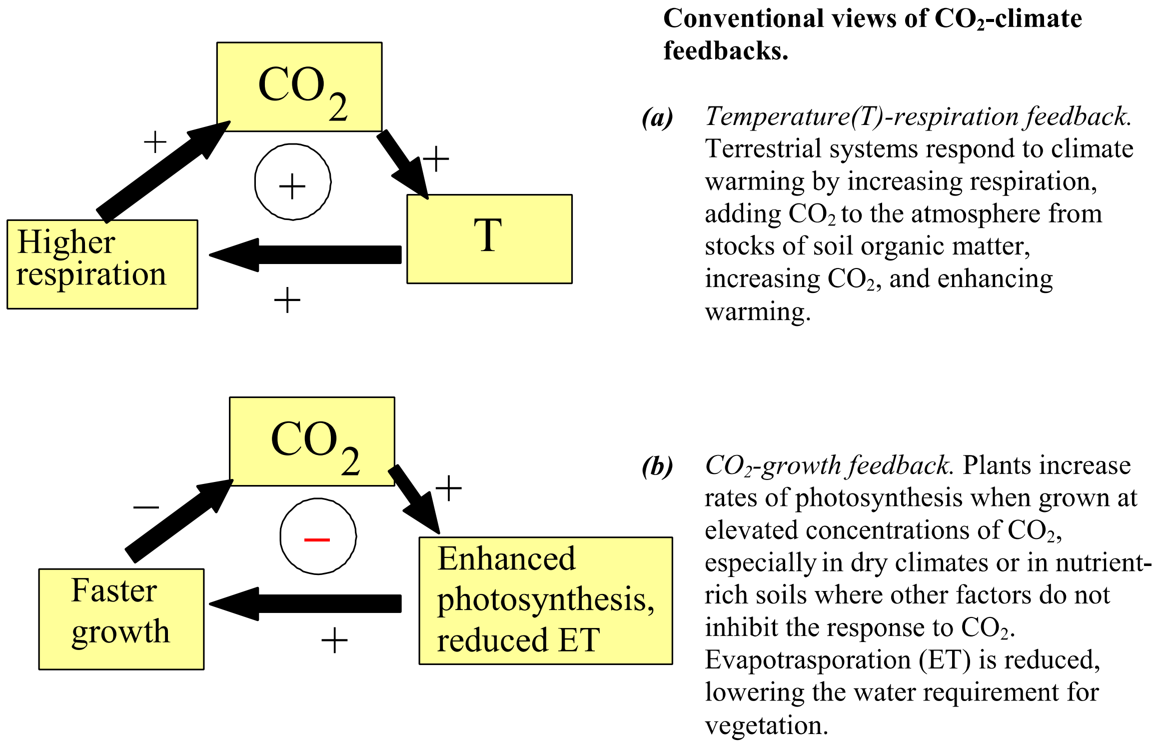


Fig. 3. The effects of increasing CO_2 and temperature on photosynthesis and heterotrophic respiration (decomposition). As temperature increases, decomposition rates increase following a Q_{10} relationship, while photosynthesis rates increase to an optimum and then decline. Increasing CO_2 causes photosynthetic rates, other things being equal, to increase. Increased CO_2 generally leads to decreased N content in plant tissue, hence slower decomposition rates during decomposition and lower respiration rates. Elevated atmospheric CO_2 can increase carbon storage by increasing carbon fixation and by slowing decomposition.

Not new, ca 2003: **Understanding Climate Change Feedbacks,** National Research Council. 2003. *Understanding Climate Change Feedbacks*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10850.



Conventional views of CO_2-climate feedbacks.

(a) *Temperature(T)-respiration feedback.* Terrestrial systems respond to climate warming by increasing respiration, adding CO_2 to the atmosphere from stocks of soil organic matter, increasing CO_2, and enhancing warming.

(b) *CO_2-growth feedback.* Plants increase rates of photosynthesis when grown at elevated concentrations of CO_2, especially in dry climates or in nutrient-rich soils where other factors do not inhibit the response to CO_2. Evapotrasporation (ET) is reduced, lowering the water requirement for vegetation.

FIGURE 7.1 Climate-land biosphere feedback processes: Conventional view.

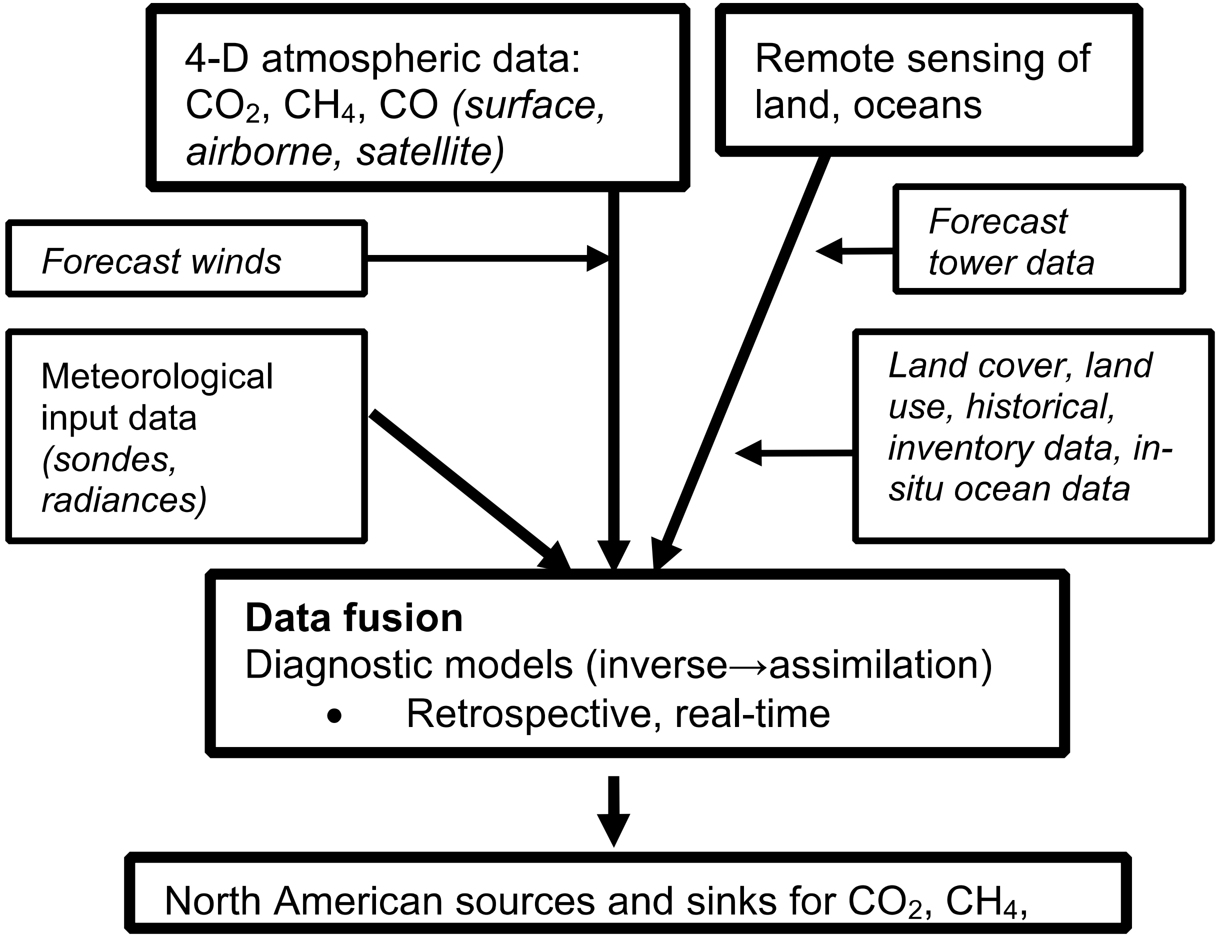
Today: γ

Today: β

But we can chase these questions way further back:

Hall CA, Ekdahl, CA, Wartenberg DE. A fifteen-year record of biotic metabolism in the Northern Hemisphere. Nature. 1975 May;255(5504):136. Used the seasonal cycle of CO_2 to estimate β.

The recommended approach in 2003 … still doesn’t look too bad



4-D atmospheric data: CO_2, CH_4, CO *(surface, airborne, satellite)*

Remote sensing of land, oceans

Forecast winds

Forecast tower data

Meteorological input data *(sondes, radiances)*

Land cover, land use, historical, inventory data, in-situ ocean data

Data fusion
Diagnostic models (inverse→assimilation)

- Retrospective, real-time

North American sources and sinks for CO_2, CH_4,

What’s new, why and how might we make progress on these questions that have engrossed the community for decades?

New observations –measurement networks and space systems we couldn’t even have imagined,

New computing paradigms, assimilation and advanced coding

Urgency!

Challenge 1: NEE is a small difference between two much larger fluxes:

- This structure results in a complex and unstable set of equations and serious measurement challenges.
- The component fluxes must be known with great precision to determine the sensitivity of the coupled processes.
- The component processes, GPP, Respiration and Fire are not independent but affect each other through nutrient cycling, demography and residence times.

Challenge 2: The biosphere is heterogeneous on all scales.

- Different vegetation, soil, water mass, disturbance and management regimes materially change the behavior of ecosystems.

- History matters: terrestrial and marine ecosystems preserve the memory of their evolutionary, disturbance and recent biophysical conditions and so behavior cannot be predicted entirely from first-principles equations.

- Sparse and biased land and ocean sampling means ”upscaling” is challenging and models are based on biased and incomplete information.

Challenge 3: Scale, feedbacks and coupling

- Ecosystems are physically coupled to the atmosphere on weather and climate timescales by matter and energy fluxes so predicted changes can create new forcing, limiting the range of analysis with land or ocean models alone.

- Terrestrial ecosystems respond nonlinearly to atmospheric forcing and may require resolution of very small-scale and transient climate events (weather) or their statistics realistically to simulate responses, that, is the most extreme forcing may drive a disproportionate share of the response.

Challenge 4: Species

- Like it or not, the biosphere is composed of millions of interacting species, each with distinctive functional characteristics.
- How much can these be simplified? Today, we collapse ~40,000 tropical tree species into 1 plant functional type, treating the ~20,000 Amazonian, 6000 African and ~14,000 Asian species as if they were a single entity, even though these environments differ and these trees have been evolutionarily isolated since the breakup of Gondwanaland.
- The hypothesis of optimality-that functional characteristics can be entirely predicted from correlation with stable environmental conditions—is certainly first order useful but is it useful or catastrophically misleading on climate change timescales? Does high species diversity promote near-optimal or complex non-linear responses?
- How do invasive species interact with orderly community processes as seen in the paleorecord?

Rising to the challenges with new observations

- Today’s ecosystem models are “first-principles” based (eg, LUE, NPZ, etc), initialized, parameterized and run with limited data on the functional diversity of life on Earth, as organized by the biophysical environment, disturbance history and evolutionary constraints and biased towards the better understood autotrophic than the more cryptic and less charismatic heterotrophic processes.

- Models have developed with sparse and biased data, resolving some regions (mid-latitudes) and processes (GPP) more than others.

- These biases reflect sampling and methodology available over the past few decades as well as the dominant satellite products, NDVI and ocean color, that both emphasize photsynthesis.

- Models written before GPP and NEE data were available, and litter decomposition data more nearly balanced biomass and NPP collections emphasized decomposition and turnover time more than current work (eg, Rothhampsted, Century, DNDC, Linkages).

- Available data constrain modelers practically and conceptually!

The new world of data and data assimilation

- New observations constrain a wider range of scales and processes.
- New satellite data integration creates “flux towers in the sky”.
- New land and ocean remote sensing will provide direct geospatial data on functional diversity of land and ocean plants.
- Data assimilation for land and ocean models is maturing and allows incorporation of data reflecting functional diversity and function into models for state and parameter estimation.
- Taking full advantage of these data and DA methods requires new model structures computationally and conceptually.

Charge to the workshop

- Today’s models reflect the data and tools, with their emphases, biases and uncertainties, available yesterday!
- What will a land or ocean model built with today’s and tomorrow’s observations look like?
- What role will space-based data play?
- What are the challenges of data assimilation for such models?
- We should capture these ideas as specifically as possible!
- We want to report these ideas in a review paper, hopefully to become a seminal guide to the next era of land and ecosystem models and their linkage to the rest of the Earth System.
- We want to report the implications of these modeling notions back to the observational community as a guide to new missions, networks and observables.