Leaky Sequestration in the Greenhouse: Lessons from a Model of the Global Carbon Cycle

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Outline for Today

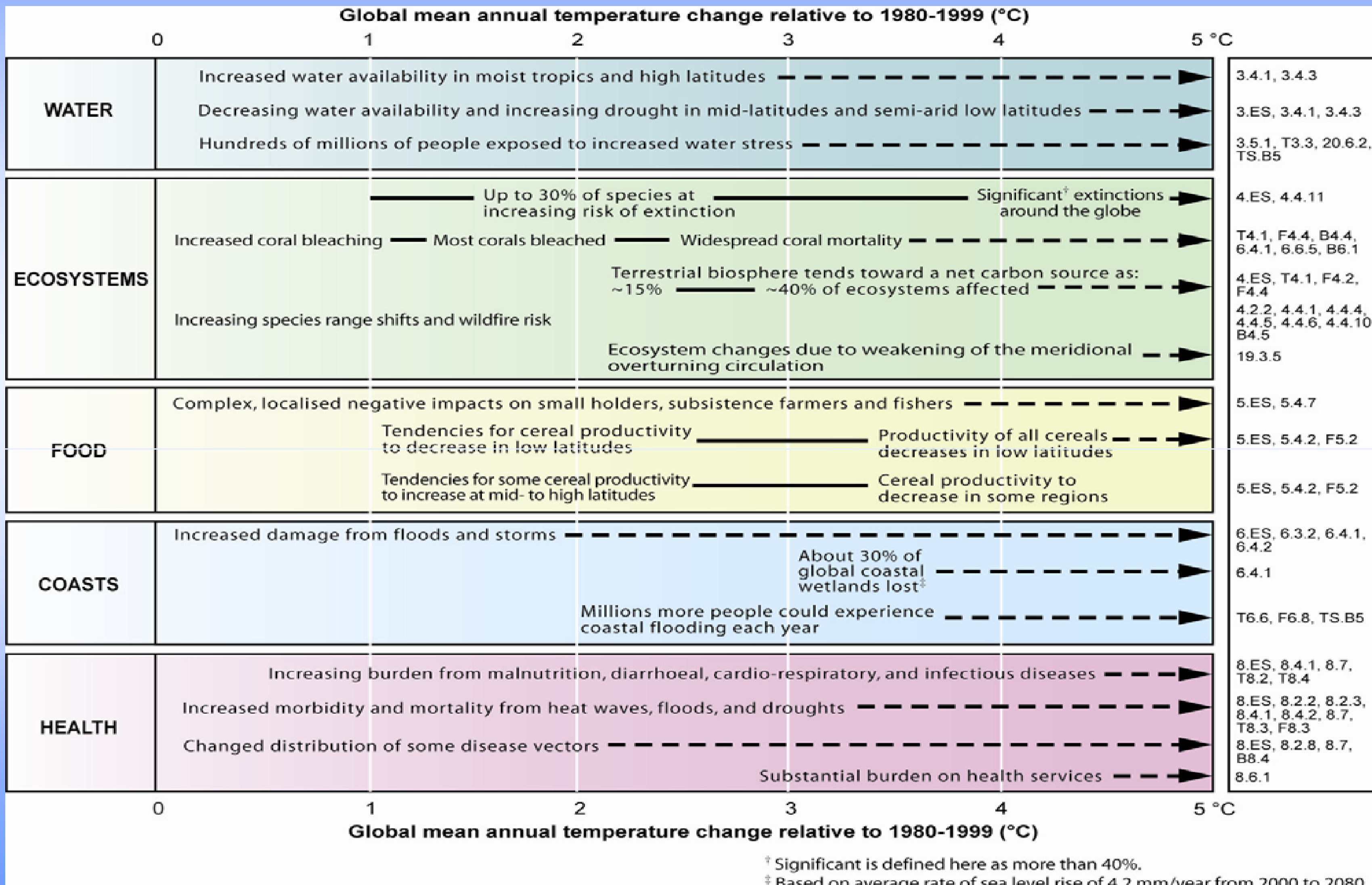
- Atmospheric stabilization
- The future role of CCS
- The problem of leaky sequestration
- Mitigating leakage
- Simple lessons for policy

- <u>Key questions</u>: What is an appropriate measure of overall leakiness? To which system parameters is the outcome most sensitive? How much confidence must we have initially to advocate large-scale deployment?

Article 2 of 1992 U.N.F.C.C.C.

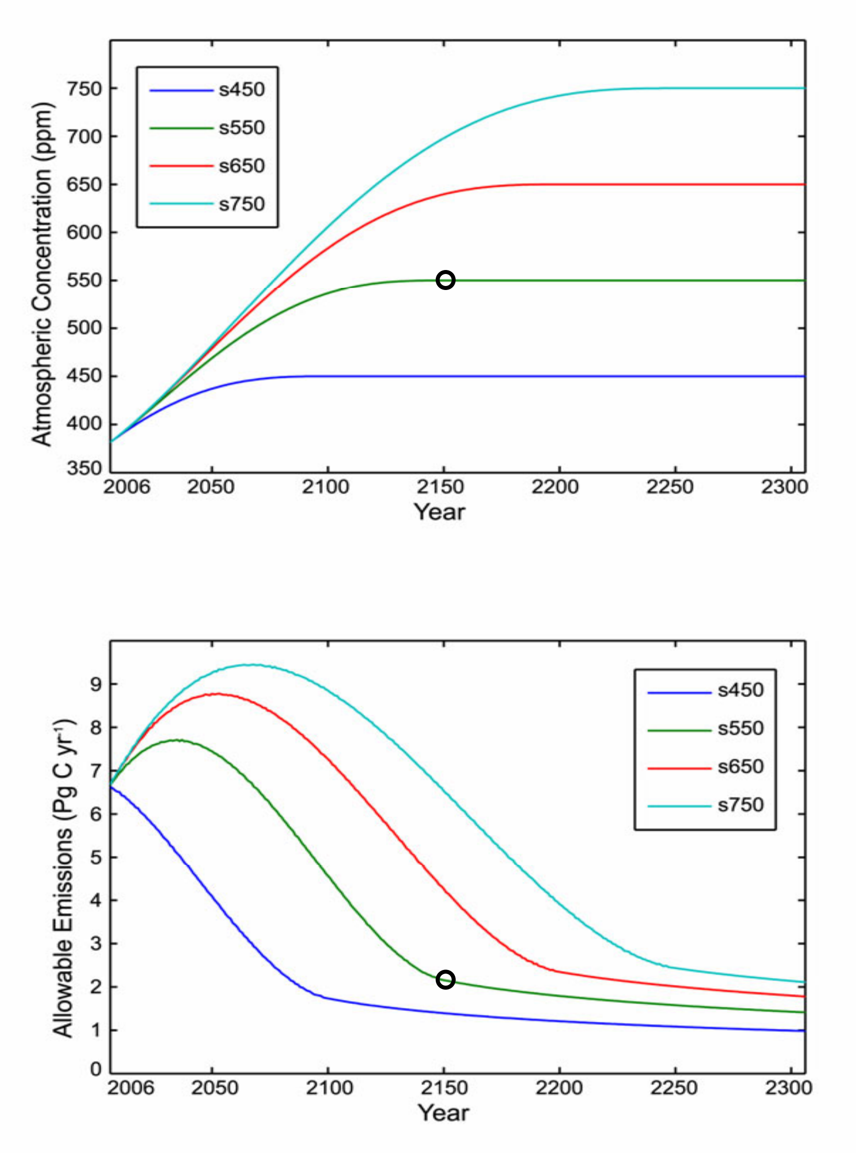
"The ultimate objective of this Convention… [is to achieve] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent **dangerous anthropogenic interference** with the climate system".

What is Dangerous?



IPCC AR4, WG II 2007

Implications for Emissions



Stabilization in the 450 to 550 ppm range is probably necessary to avoid the most dangerous outcomes (e.g. ice sheet collapse).

We can use a carbon cycle model (HILDA) to back out **net** allowable emissions trajectories:

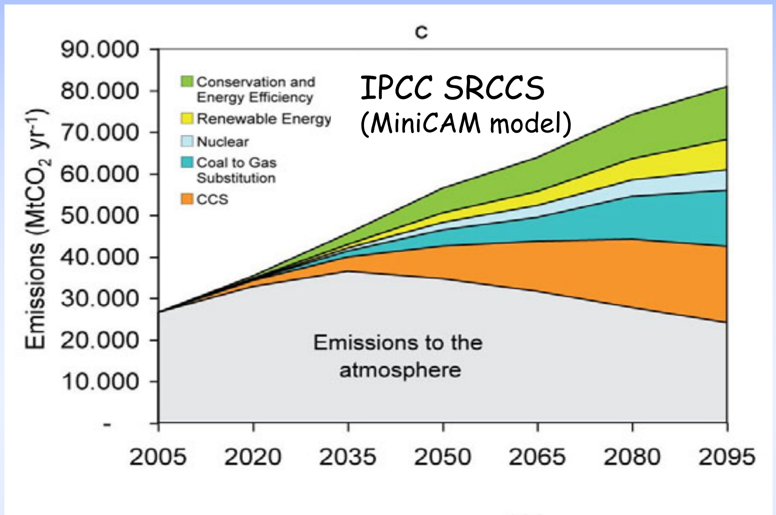
$$A' = E - F \rightarrow E = A' + F$$

In classic stabilization scenarios, emissions decline quickly after near-term peak.

In long run (post-stabilization), emissions release must not exceed uptake by natural sinks ~1-2 Pg C yr^{-1}.

CCS Deployment

Economic Importance: Projections of future energy use typically assume significant entry of CCS under carbon policy. The affordability of carbon mitigation is directly tied to the availability of CCS.



Technological Readiness: Capture, transport and storage technologies are separately commercial at full-scale. Integration of these technologies is underway in several large-scale projects.

Political Interest: Sen. Kerry's "Clean Coal Act" would require new coal-fired power plants to be equipped with CCS technology. Would target ~150 new plants that have been proposed.

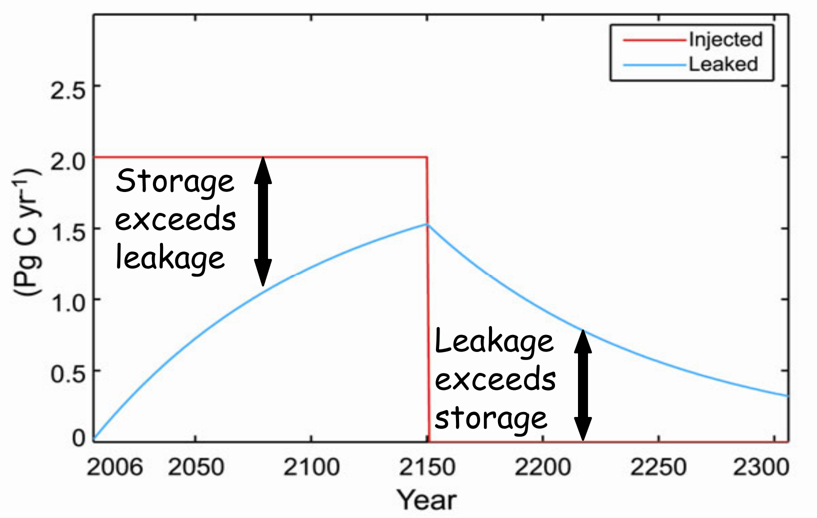
Toward a Coherent View of Leakage

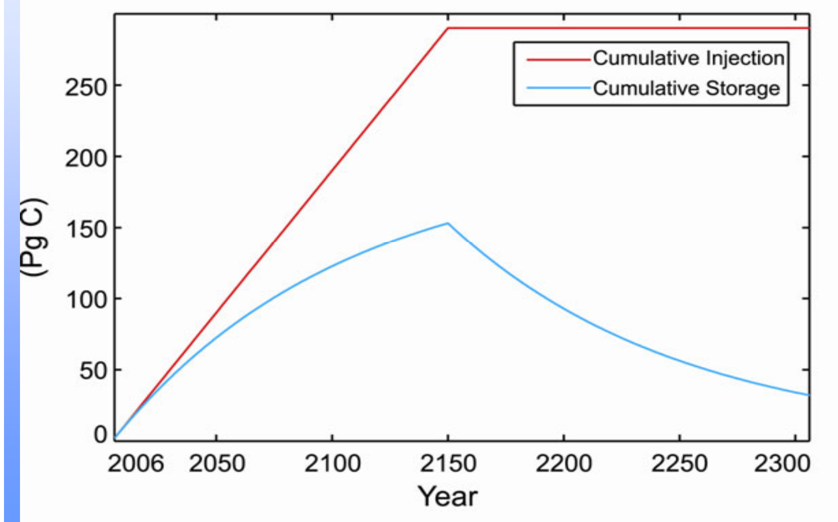
- Working assumption: Some emissions are unavoidable in the economy and will be very difficult to displace.
- If CCS is part of the energy mix, then future emissions will be constrained by leakage (net emissions and leaked carbon must sum to < ~ 2 Pg C yr^{-1} after stabilization).
- Different reservoirs are characterized by different storage timescales: Highest for geologic storage (millennia or longer); lower for terrestrial and oceanic storage.
- Leakage must not place unrealistic demands on future mitigation.
- Our goal: To explore the sensitivity of the leakage trajectory to the initial reservoir integrity, the nature of the loading, and our ability to learn through experience. And more generally, to impel the CCS community to define appropriate performance metrics.

Might our initial premise be wrong?

- After all, future technology could diminish the burdens imposed by leakage:
  - First possibility: Complete de-carbonization of energy becomes possible, reducing the need for significant emissions "headroom".
  - Second possibility: Complete de-carbonization of energy does not become possible, but technologies to capture carbon directly from air become widely available; carbon leaked from a storage reservoir could be captured and re-injected.
- The problem is that we can't count on these now.
- Useful Analogy: Harmful effects of radioactive waste could be mitigated by future medical advances, but few would view this strategy as a viable alternative to safely storing today's waste.

A Simple Model of Leakage



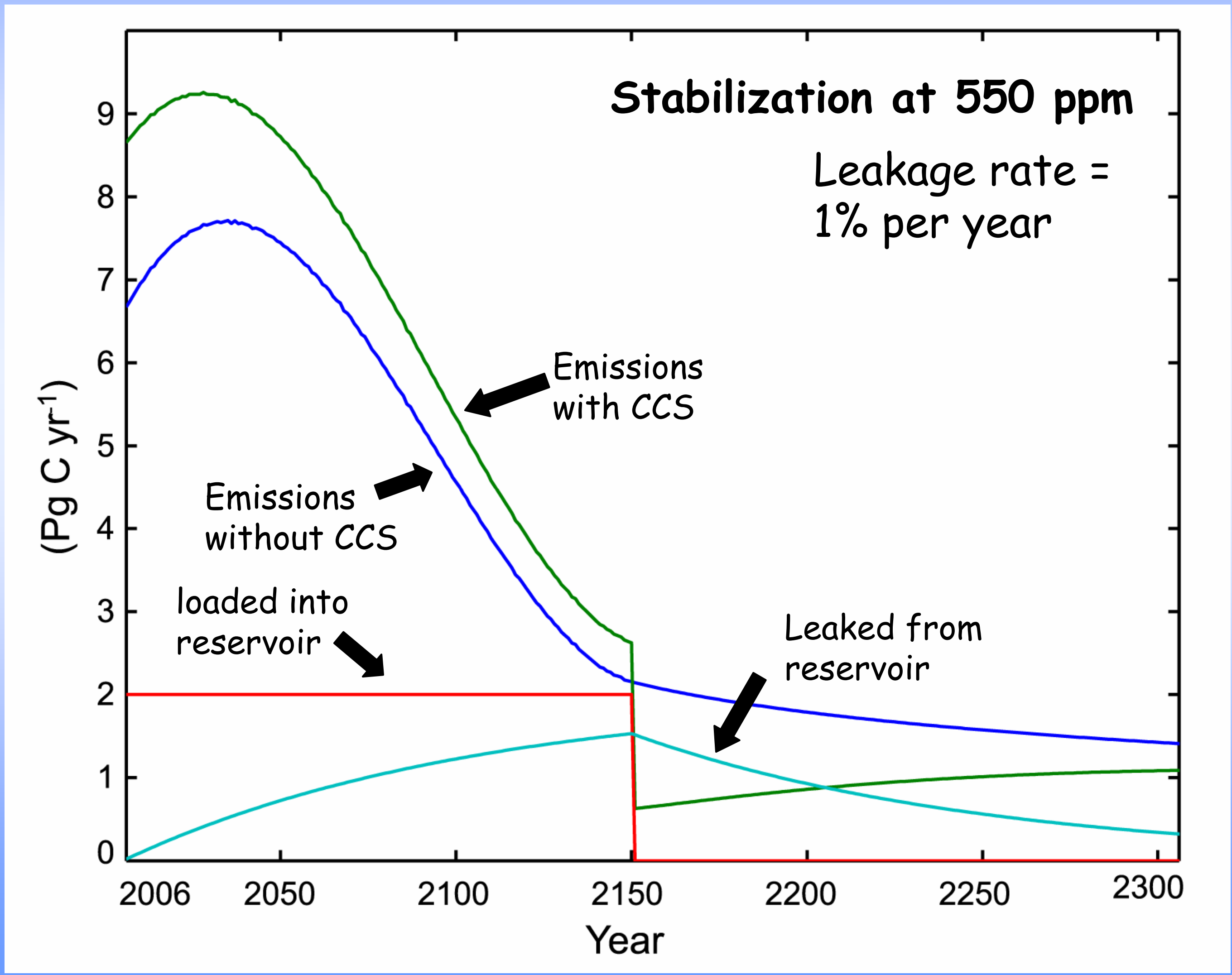


Assume constant loading of 2 Pg C yr^{-1} for ~150 years & that carbon leaks from a storage reservoir at a constant rate of 1% yr^{-1}.

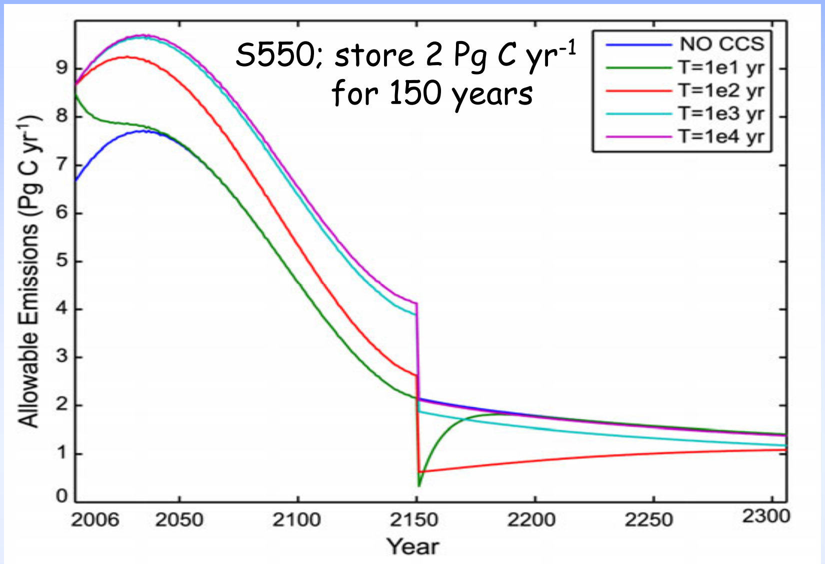
In this world, there is a period in which net storage is positive (net leakage is negative) followed by a period in which net storage is negative (net leakage is positive).

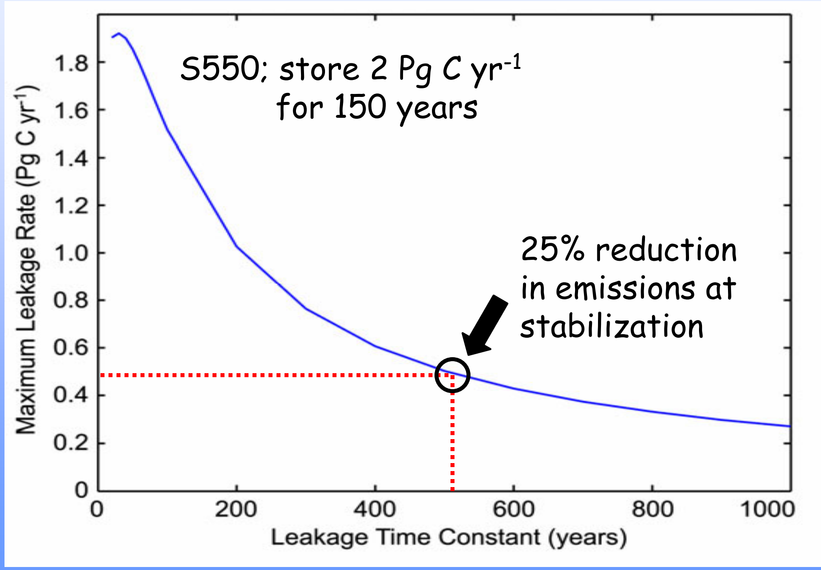
<u>Two metrics</u>: **Net leakage** measures the impact on the **global environment** (allowable emissions). **Gross leakage** is related to impacts on the **local environment** (e.g. groundwater). <u>In this example, they are the same!</u>

The Global View: Bargaining with the Future



How leaky is too leaky?





<u>When leakage is very fast</u>:

The immediate **benefits** are **low** and the future **costs** are **high**.

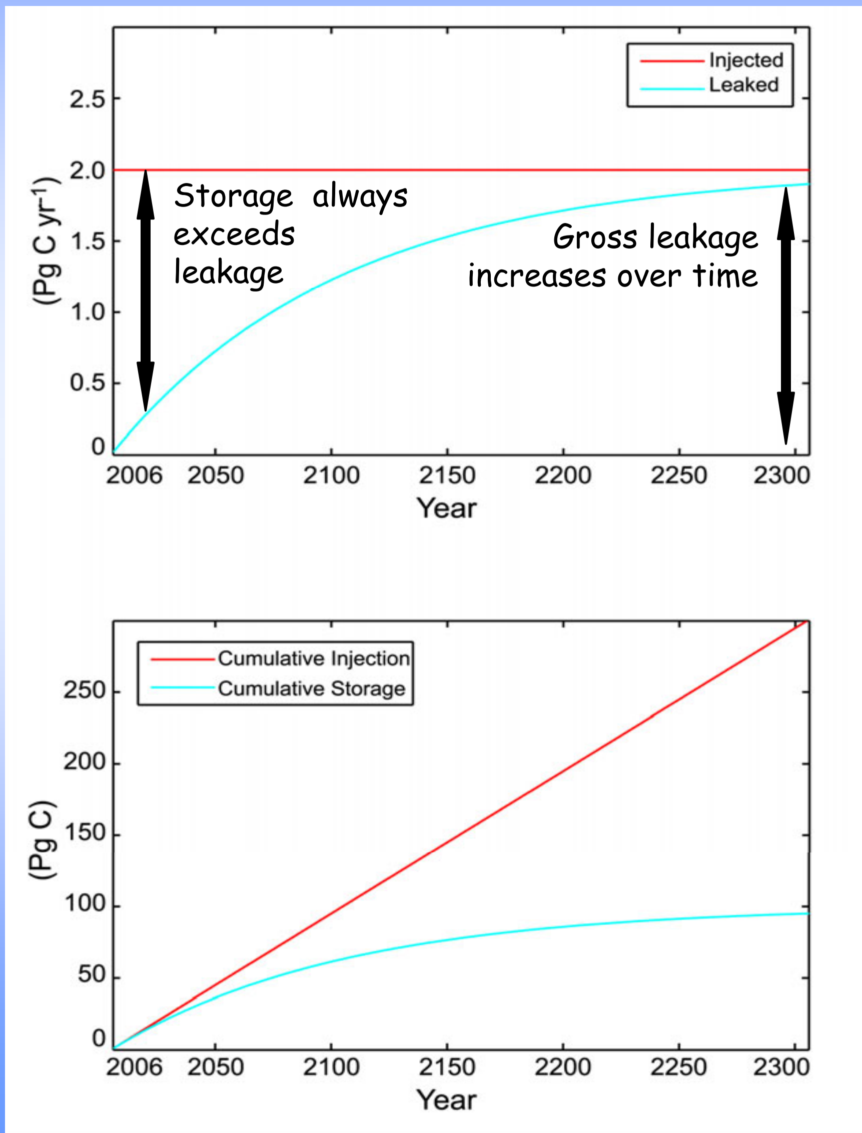
For τ = 10 years, the maximum leakage rate is ~2 Pg C yr^{-1}, or nearly 100% of the allowable emissions at stabilization.

<u>When leakage is very slow:</u>

The immediate **benefits** are **high** and the future **costs** are **low**.

For τ = 1000 years, the maximum leakage rate is ~0.2 Pg C yr^{-1}, or about 10% of the allowable emissions at stabilization.

What if we don't stop at 150 yrs?



Assume constant loading of 2 Pg C yr^{-1} **forever** & that carbon again leaks from a storage reservoir at a constant rate of 1% yr^{-1}.

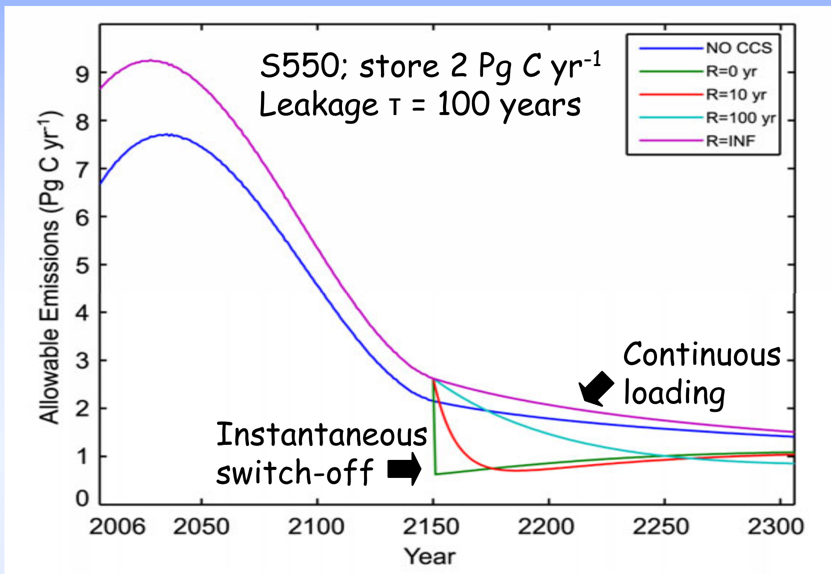
The good news: **Net leakage** is always **negative** (net storage is always positive).

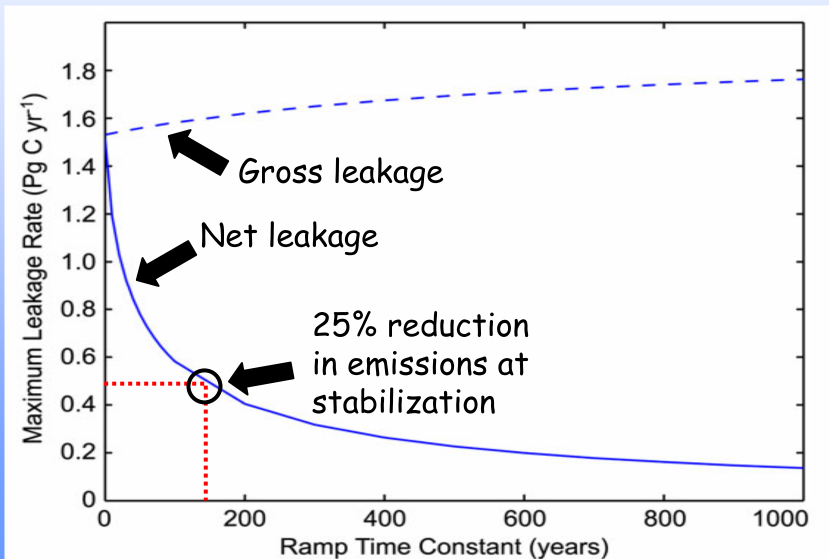
The bad news: **Gross leakage** is **positive** and increases with time (toward a final value).

The choice of metric turns out to be important here.

Are we prepared to leave a burden of this magnitude to future generations?

A More Realistic Possibility





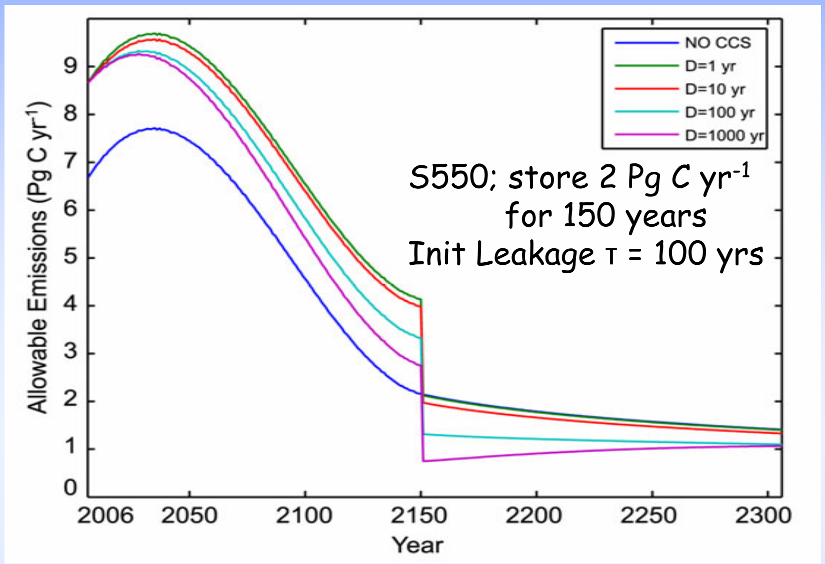
One plausible alternative would be to gradually decrease the loading as our need for it diminishes.

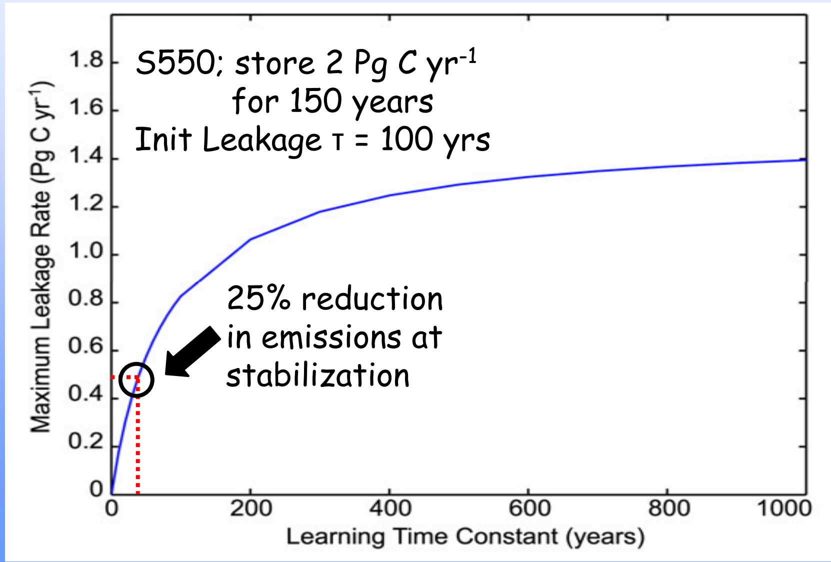
This would still require some future commitment to CCS and would also shift the period of maximum leakage farther into the future.

Net Leakage: In order to limit the reduction in allowable emissions to 25%, the ramp period must exceed ~150 years. To limit the reduction to 10%, it must exceed ~600 years.

Gross Leakage: Only gets worse as the ramp period increases, because more carbon is in the ground at later times.

What if we get smarter?





What if we get smarter about where/how to store carbon?

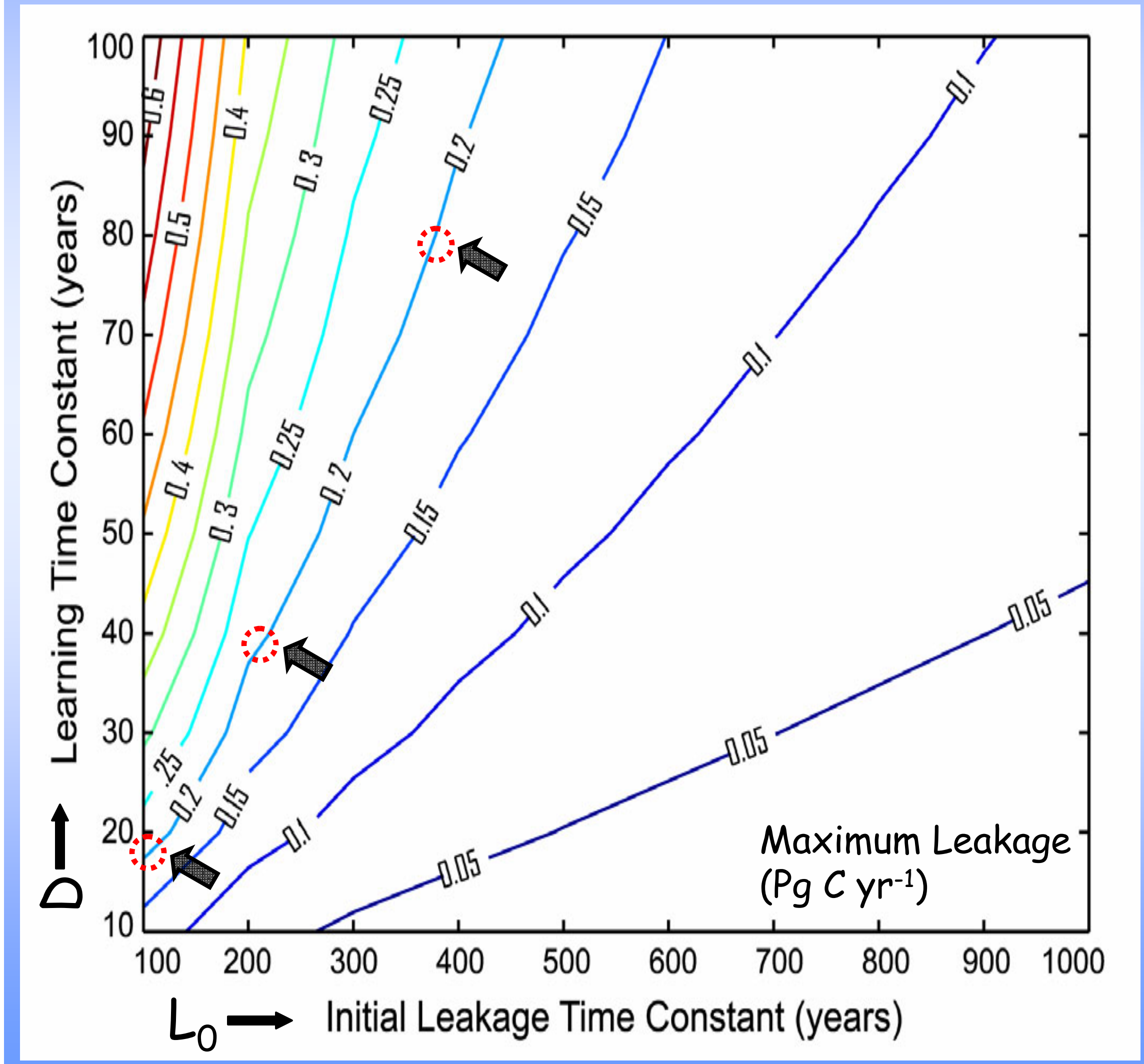
This reduces the need to have very small leakage rates today.

<u>But</u>, we would need to learn quickly:

In order to limit the reduction in emissions to 25%, the learning time constant (time to first doubling of average reservoir integrity) must be ~20 years.

To limit the reduction to 10%, the learning time constant must be decreased to ~10 years.

Leakage-Learning Tradeoff



As before, assume loading of 2 Pg C yr^{-1} for ~150 yrs.

Assume that the leakage time constant is again a function of time (learning):

$$\Gamma = L_0*(1 + t/D)$$

Maximum (net or gross) leakage is achieved when CCS is turned off in 2150.

The world defined by L_0=100 & D=10 is roughly equivalent to the world defined by L_0=1000 & D=INF (0.1 PgC/yr isoquant).

Moving Forward

- As with any new technology, the future success of CCS will depend on public approval of early efforts.
- Performance standards will need to be developed early on for the purposes of permitting.
- Ideal metrics will take a long view of the leakage problem.
- The more confident we are about learning quickly, the more permissive we can ask the public to be about the leakiness of early projects.
- Claiming too much capability too soon risks failure and jeopardizes public support.
- At the same time, early permissiveness must not compromise overall safety.