Human Perturbations to the Global Carbon Cycle

Mitigation Opportunities

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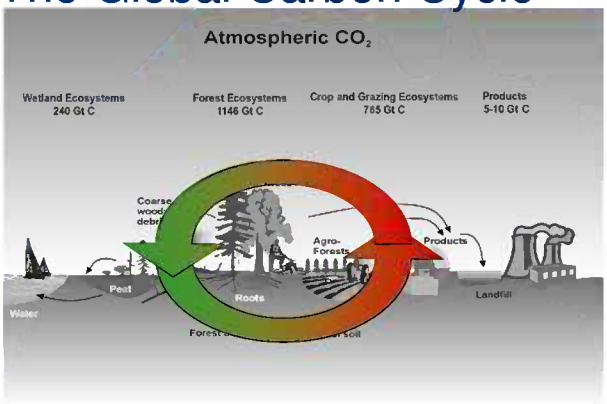
Retired (!)

Setting the stage: Overarching Questions

- **Why are we concerned about greenhouse gases?**
  - How much damage will climate change do, how much of this can we avoid, and what is an acceptable level of damage? I.e.,
    - Mitigation, in terms of
    - Impacts and
    - Adaptation
- **Key: understanding the link between the global carbon cycle and climate change** … to answer:
  - How will rates of atmospheric C accumulation change?
  - What can humans do to reduce sources, increase sinks?
  - Can the fluxes causing the atmospheric accumulation be controlled, while maintaining other essential goods and services?

The Global Carbon Cycle



Exchanges:
60 GtC/yr (land),
70 GtC/yr (ocean)

C is **cycled**, not permanently stored

A natural cycle that has operated for at least 4 glacial cycles

6

Provocative insight: Kleidon *Climatic Change* 2004

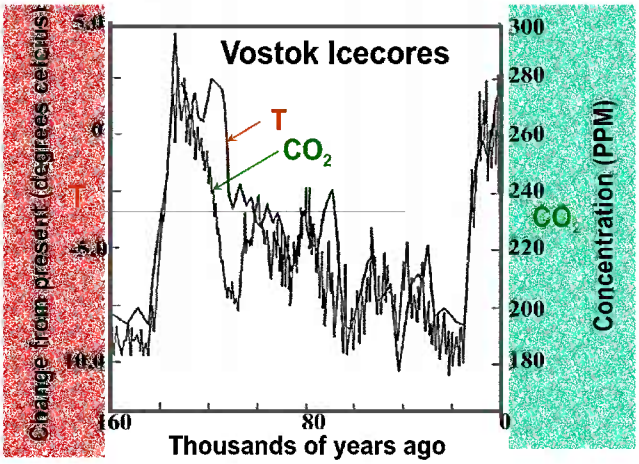
Linkages between C and Climate

- A surprising amount of information about the past is contained in the annual layers of glacial ice:
  - Debris provides a record of human response to changes in climate:
    - e.g., perhaps recording the failure of the Viking settlements in Vinland and Greenland - believed to be due to the onset of the Little Ice Age

Linkages between C and Climate

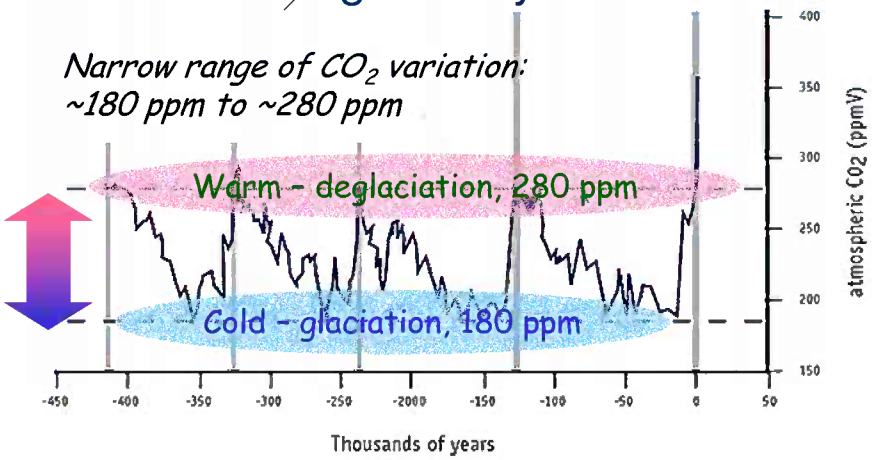
- A surprising amount of information about the past is contained in the annual layers of glacial ice:
  - Debris records human response to changes in climate:
  - Gas bubbles record past linkages between CO2 and T:

CO_2 and T broadly in step

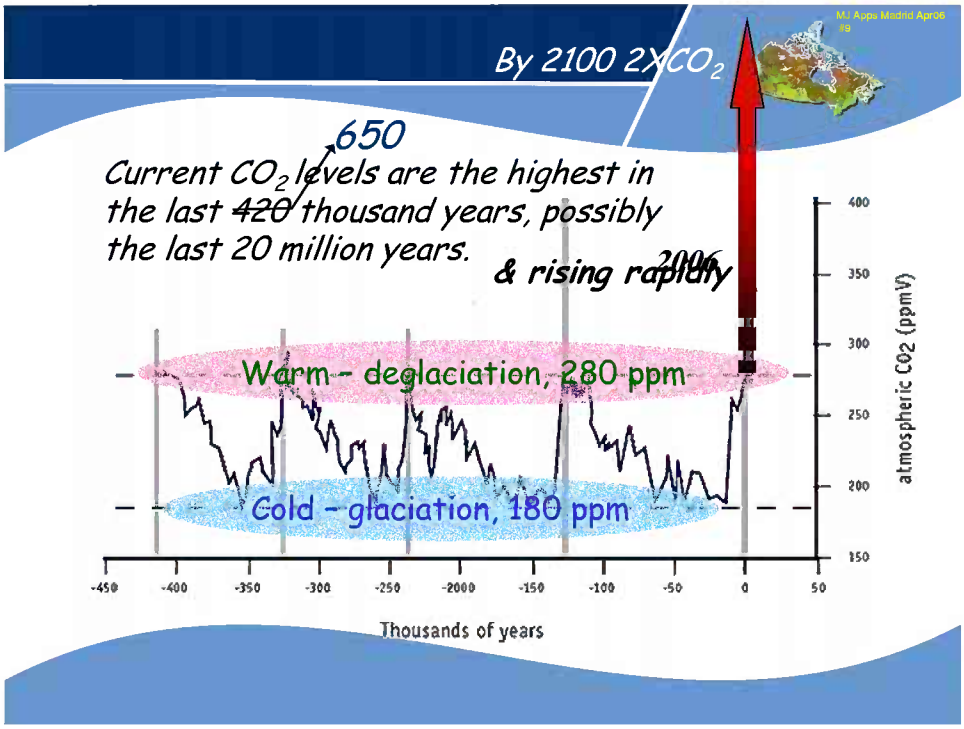


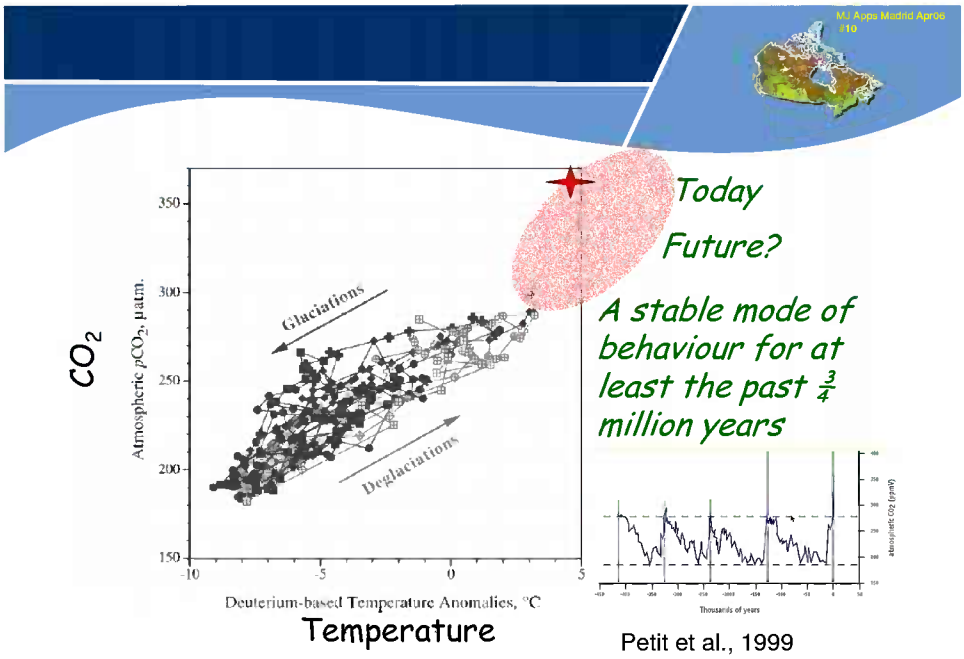
Over at least 4 ~~6~~ glacial cycles

Narrow range of CO_2 variation: ~180 ppm to ~280 ppm



Petit et al., 1999





Petit et al., 1999

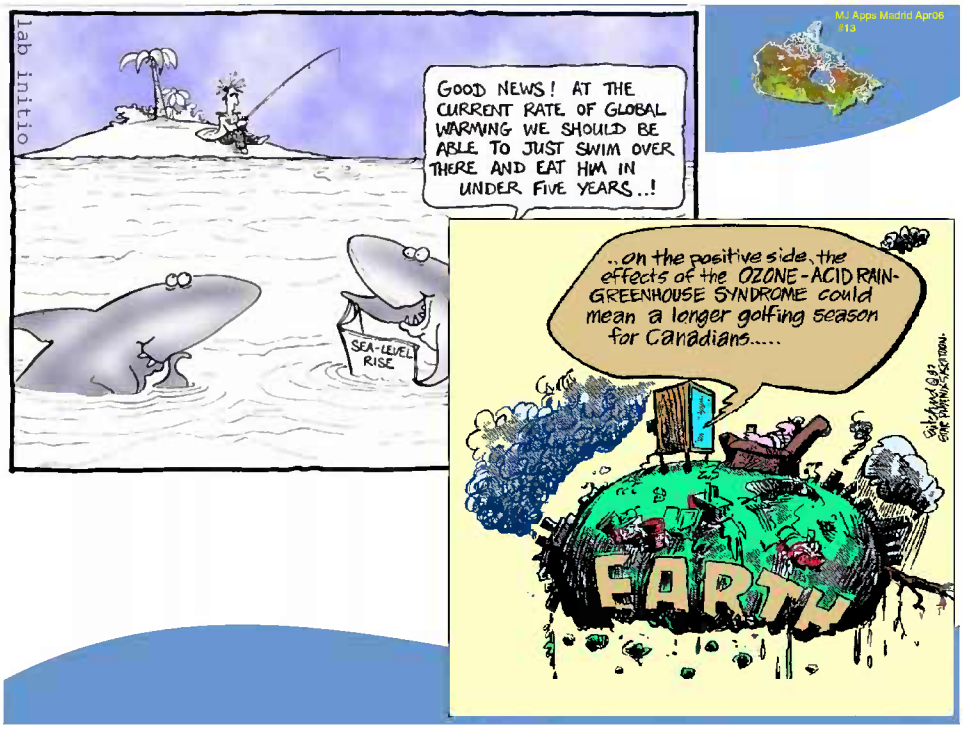
Falkowski et al., 2000

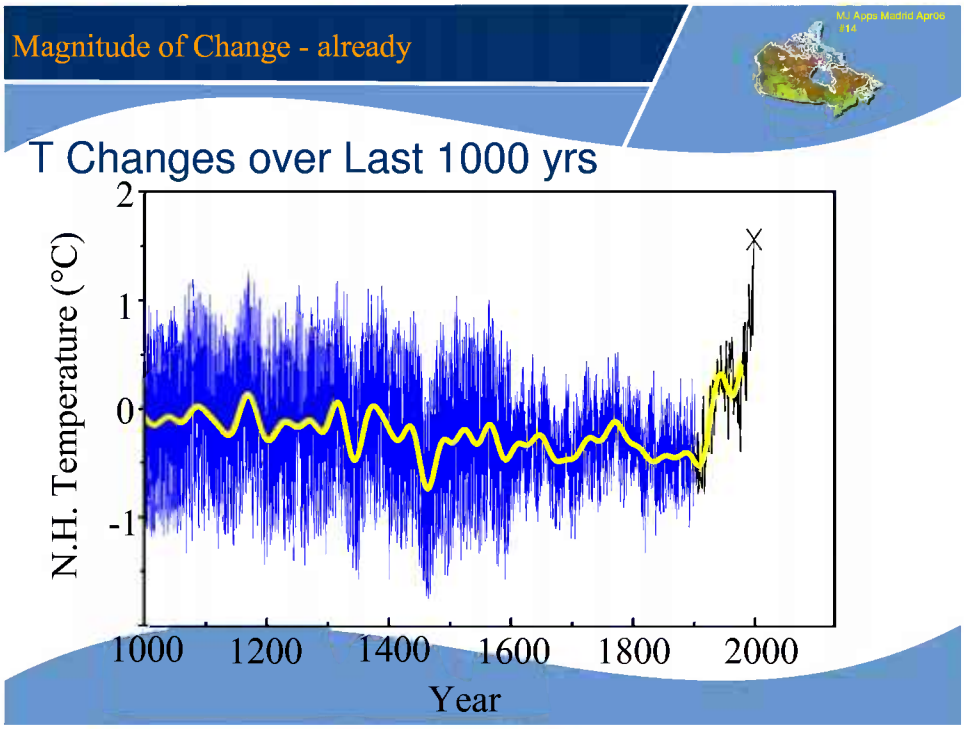
So what?

- Article 2 of UNFCCC: objective is …

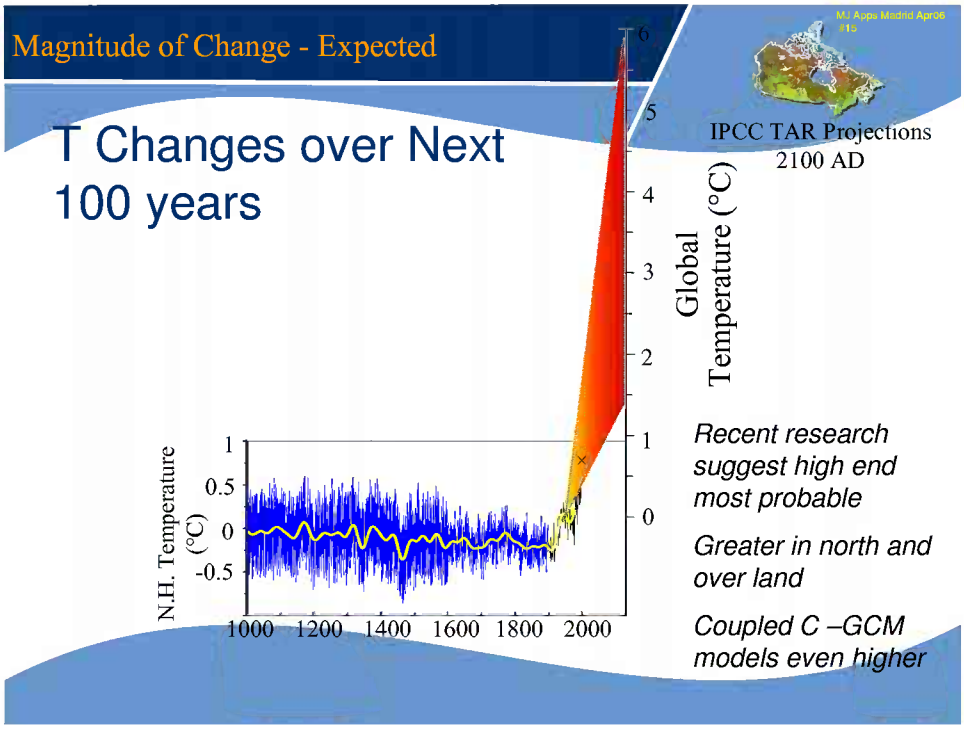
  *… stabilization of greenhouse gas concentrations in the atmosphere at a level that would **prevent dangerous anthropogenic interference with the climate system** …*

- So we need to know something about the dangers of climate change
- And, of course, defining what is dangerous is not a scientific task. It requires societal judgment, and depends on your point of view:


lab initio
GOOD NEWS! AT THE CURRENT RATE OF GLOBAL WARMING WE SHOULD BE ABLE TO JUST SWIM OVER THERE AND EAT HIM IN UNDER FIVE YEARS..!
SEA-LEVEL RISE
..on the positive side, the effects of the OZONE-ACID RAIN-GREENHOUSE SYNDROME could mean a longer golfing season for Canadians.....
EARTH


Magnitude of Change - already
T Changes over Last 1000 yrs
N.H. Temperature (°C)
2
1
0
-1
1000
1200
1400
1600
1800
2000
Year

Magnitude of Change - Expected



Dangerous?

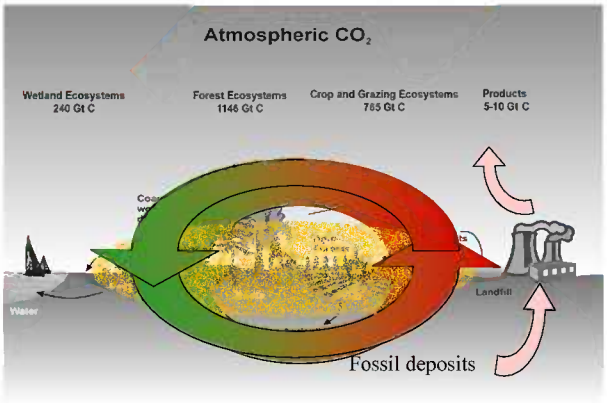
Literature suggests:

- *… there seems to be a convergence in the literature towards an **upper limit of 2 C increase in mean global T** above industrial levels …. but both lower and higher T values have been argued as well.*
- ***And**: we have witnessed **nearly 1 C change already** (0.17 C/decade since 1979),*
- ***And:** we are **committed to ~0.1** C/decade for decades to come (even if we stop all emissions now)*
- ***And:** warming over **land is ~ 0.25 C/decade** since 1979 significantly greater and faster than oceans*
- ***And:** under virtually **all** scenarios, we **will experience +2 C** in this century*

A Sustainability Issue

- What **IS** clear is that mitigation is tightly related to sustainability measures:
  "… *climate change exacerbates poverty*
  … *mitigation reduces vulnerability*"
- WG3 AR4 suggests
  climate change mitigation must be seen as an integral part of sustainable development
- Now I will look more closely at the carbon cycle and how humans are changing it

Perturbed Active Carbon Cycle

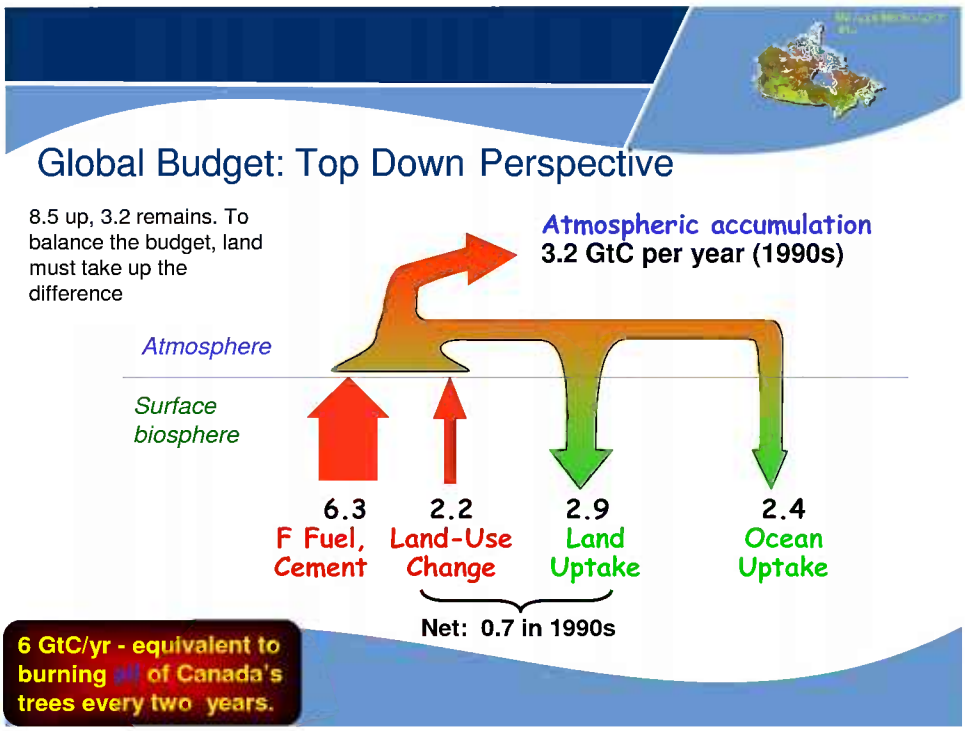


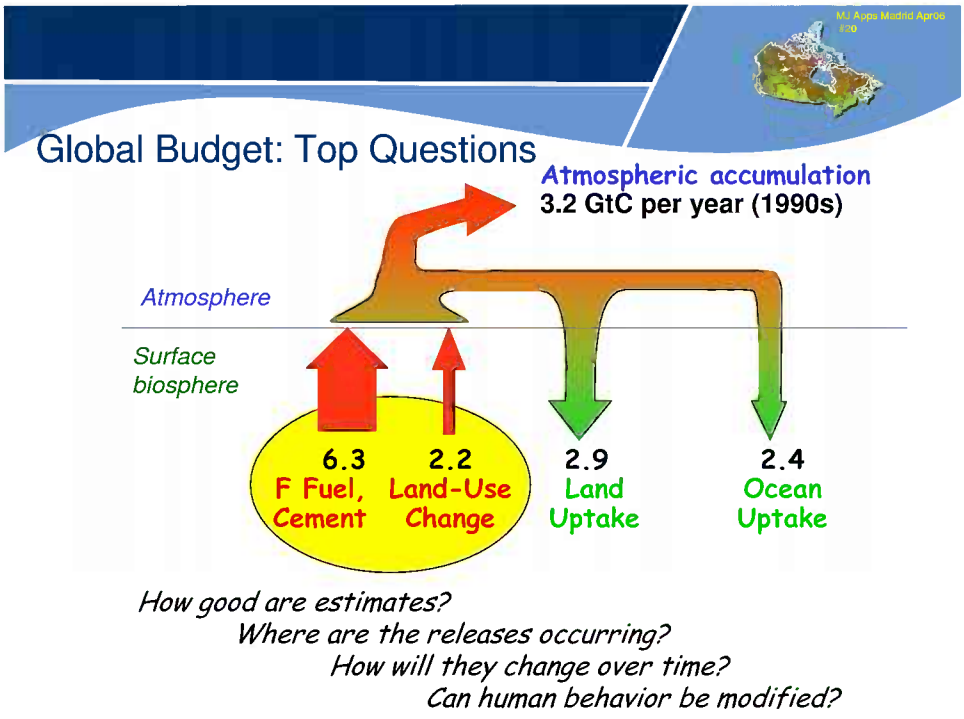
Human activity alters mechanisms of the cycle

And adds additional carbon to the active cycle

How the Earth system handles these perturbations will determine the impacts

How human activities are modified will influence the magnitude and timing of the perturbation



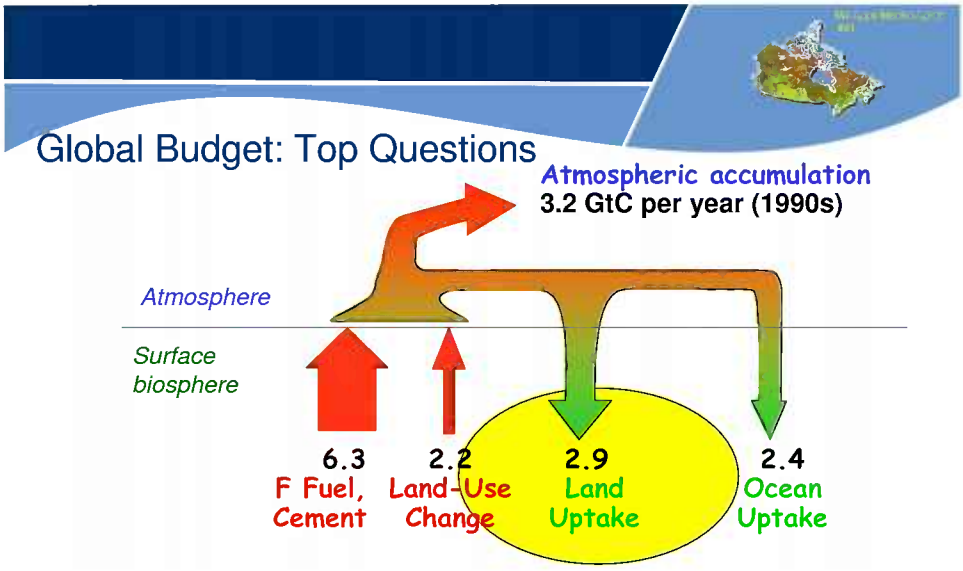


How good are estimates?

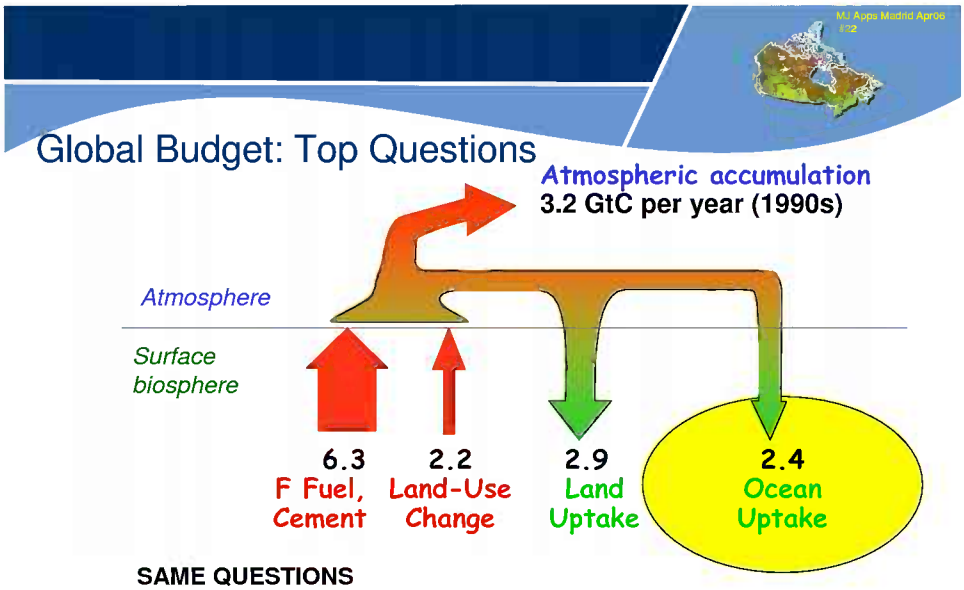
Where are the releases occurring?

How will they change over time?

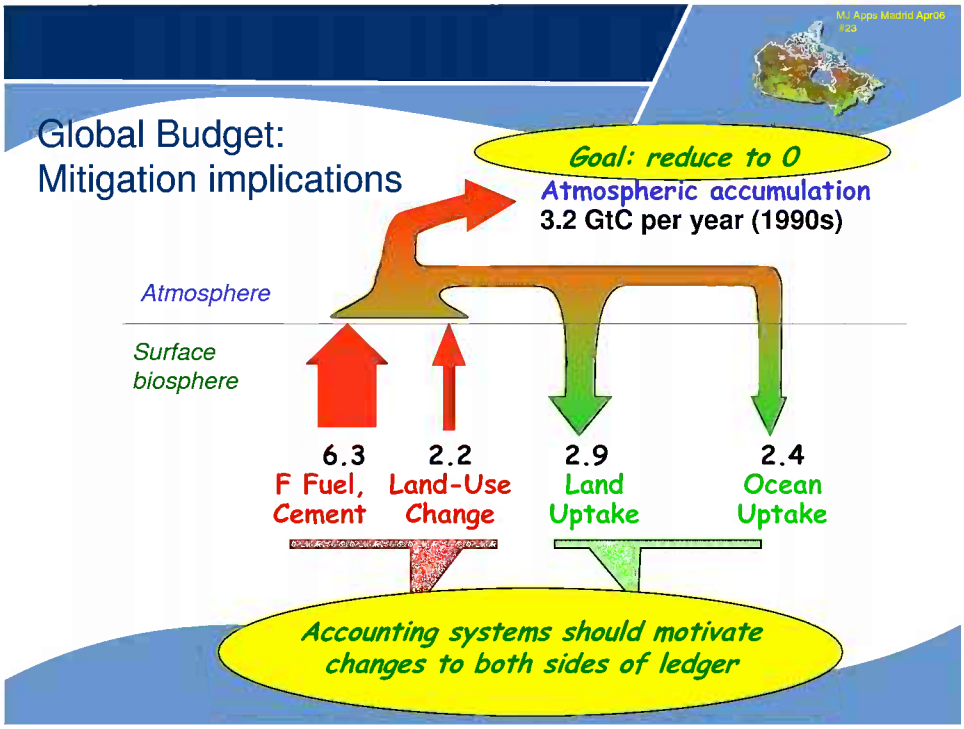
Can human behavior be modified?

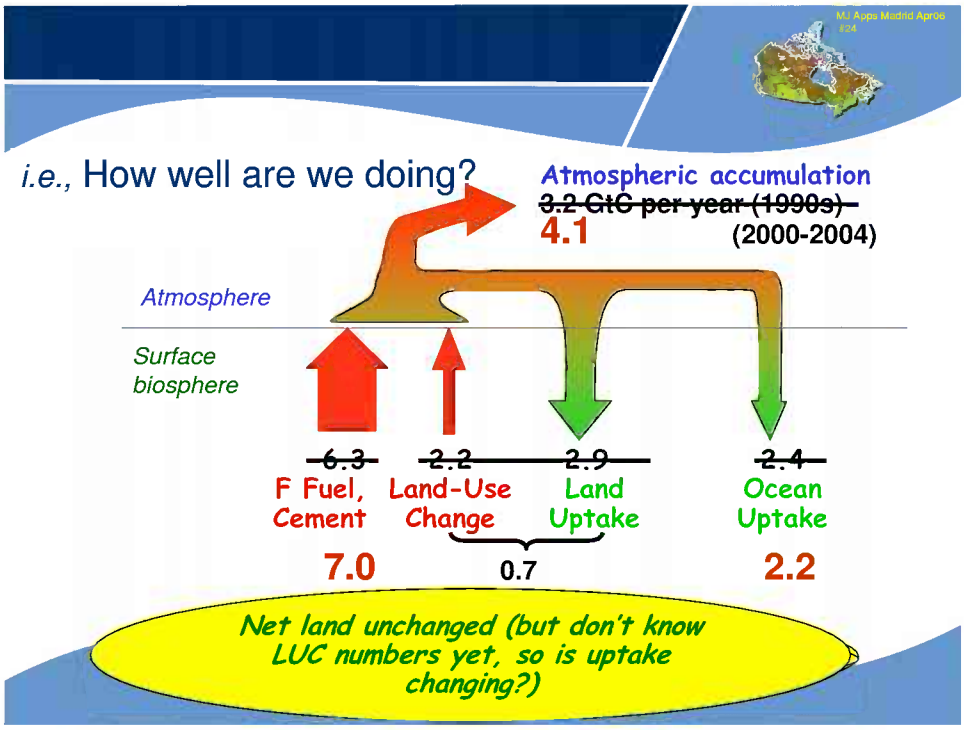


What are the mechanism responsible?
Where is the uptake occurring?
How will it change over time?
Can management influence?



SAME QUESTIONS
How good are estimates?
Where are the releases occurring?
How will they change over time?
Can human behavior be modified?

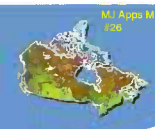

Global Budget:
Mitigation implications
Goal: reduce to 0
Atmospheric accumulation
3.2 GtC per year (1990s)
Atmosphere
Surface biosphere
6.3
F Fuel, Cement
2.2
Land-Use Change
2.9
Land Uptake
2.4
Ocean Uptake
Accounting systems should motivate changes to both sides of ledger


i.e., How well are we doing?
Atmospheric accumulation
3.2 GtC per year (1990s)
4.1
(2000-2004)
Atmosphere
Surface biosphere
6.3
F Fuel, Cement
2.2
Land-Use Change
2.9
Land Uptake
2.4
Ocean Uptake
7.0
0.7
2.2
Net land unchanged (but don't know LUC numbers yet, so is uptake changing?)

Top-down vs Bottom-up Budgets

- *Land uptake currently inferred as residual*
  - Bottom up estimates are incomplete – limited by sectors, regions, and data availability
- *Houghton reviewed recent top down and bottom up estimates and attempted to reconcile for the 1990s. He concluded*
  - Global land net uptake : net tropical source and a net northern sink,
  - Magnitudes depend on accuracy of estimates of tropical LUC
  - Both net tropical source and net northern sink appear to be **changing over time**

R.A.Houghton, 2003.
Global Change Biology 9: 500-509,

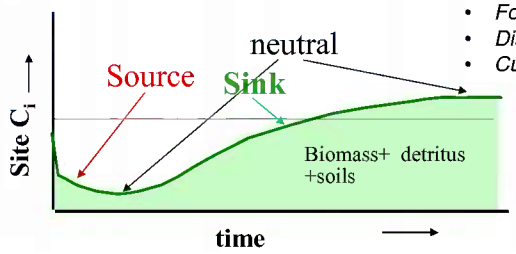


Mechanisms for land uptake

- *What we now know*:
  - ***No single region*** *is responsible*
  - ***No single mechanism*** *is responsible*
- *Rather*
  - ***Spatial mosaic of sources and sinks*** *– at many scales, across landscapes, acrcss biomes, across regions*
  - *Biological sources and sinks are often* ***autocorrelated (but with time delays)***
  - *The spatial mosaic* ***changes with time***

Although challenging, accounting systems will have longer-term applicability if they reflect these dynamics

Anatomy of LULUCF Sources and Sinks



Site dynamics, e.g.

- *Forest Stand*
- *Disturbed soils*
- *Cultivated land*

*"**Sink**" = positive slope*

"Source" = negative slope

The steeper the slope, the bigger the sink or source

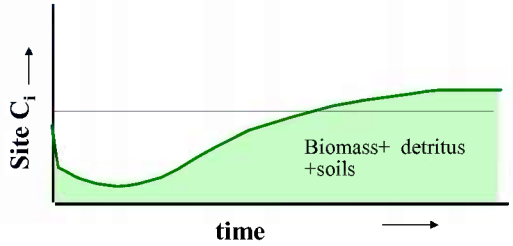
LULUCF sources and sinks are causally connected: they are auto-correlated with a time delay

*And you **don't get one without the other***

Hence a piece of land can act as a sink for part of its history and then act as source later (although some of that source may be exported)

*And vice versa – **today's source may be a future LULUCF sink***

Anatomy of LULUCF Sources and Sinks

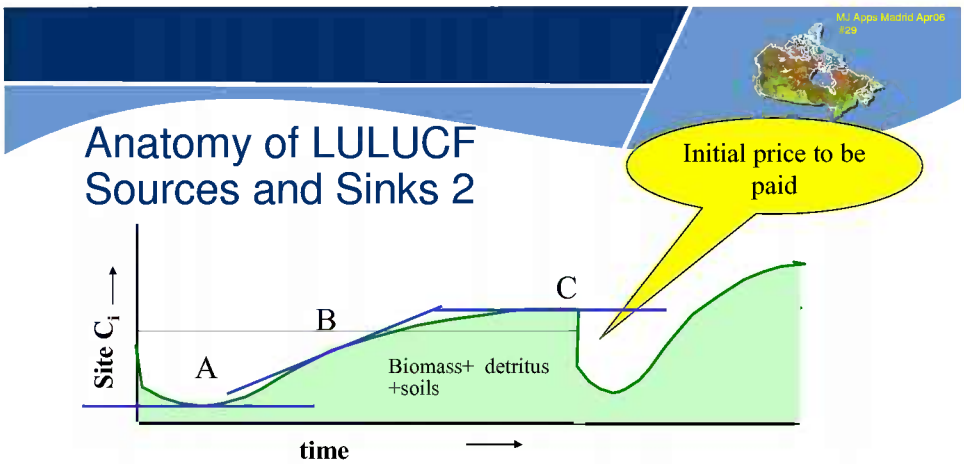


- *The size of the sink or source does not depend on the size of the pool (only the slope).*
- *The atmosphere 'sees' the **change** in pool, not its size i.e., sink x time (or source x time)*

This same sort of life cycle behavior plays out at many different scales: qualitatively the same (but with widely different time constants)

- At organism level
- At site level (e.g., stand, or soil stocks)
- At regional scale (e.g., deforestation, or abandonment)

But caution needed when extrapolating from one scale (site) to another (region) - more later

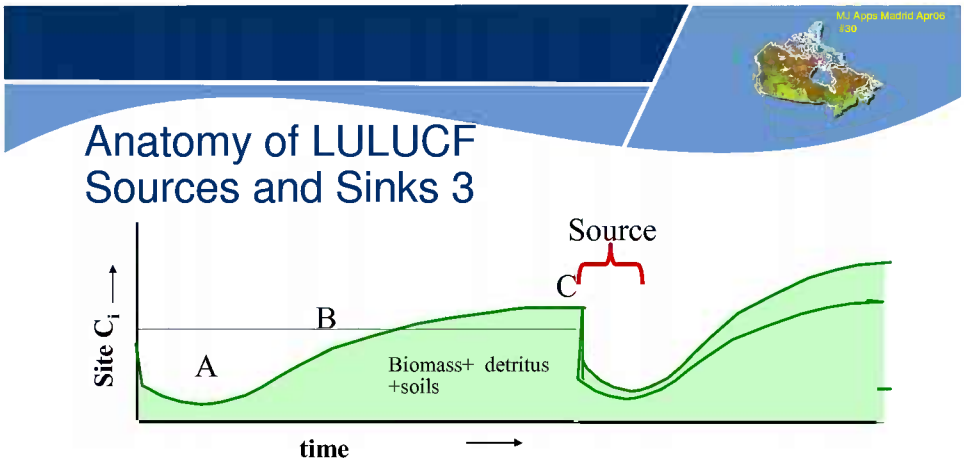


At any point in time, the present sink or source strength ***and its future potential*** *is in large measure constrained by, or predetermined by the history of the piece of land (e.g. A vs B vs C)*

At A, slope = 0, but future potential is a sink (if life cycle plays out)

At B, slope = max, future potential also a sink (if life cycle plays out)

At C, slope = 0, future potential lies in ***avoiding emissions***
Or by planting higher C species *-- eventually*



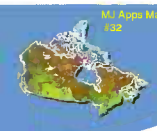
Note the asymmetry of risks and rates:
at point A (depleted stocks): Likely future sink (relatively slow)
at point C (fully stocked): Likely future source (abrupt)

Although recovery might be better (eventually)
It may also be worse if conditions have changed adversely

Importance of understanding land uptake mechanisms

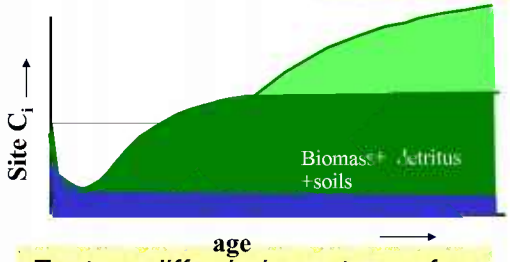
- *Different mechanisms suggest different mitigation approaches*
  - *e.g., if due to past LUC or to present environment*
- *Different mechanisms lead to different future trajectories (climate implications)*
  - *e.g., if due to legacy effects of age-structure or to CO_2 fertilization*
- *Ability to factor out direct human interventions from indirect*

Future accounting systems need to be broad enough to accommodate intrinsic differences in different parties' lands. But underlying scientific principles are identical within a broad systems perspective



Land uptake: 2 mechanisms

1. ***Changes in productivity*** *(stimulated NPP, reduced respiration) in response to CO_2, climate, nutrient, management, …*



Site dynamics, e.g.
- *Forest Stand*
- *Disturbed soils*

Increased Site fertility (Carrying capacity)

Increased growth rate, decreased decomposition

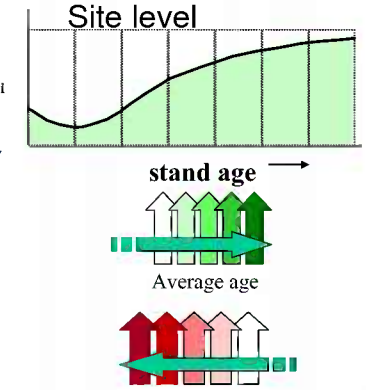
Deceased site fertility, growth rate, …

Factors differ in importance for different regions, and different histories

Land uptake: 2 mechanisms

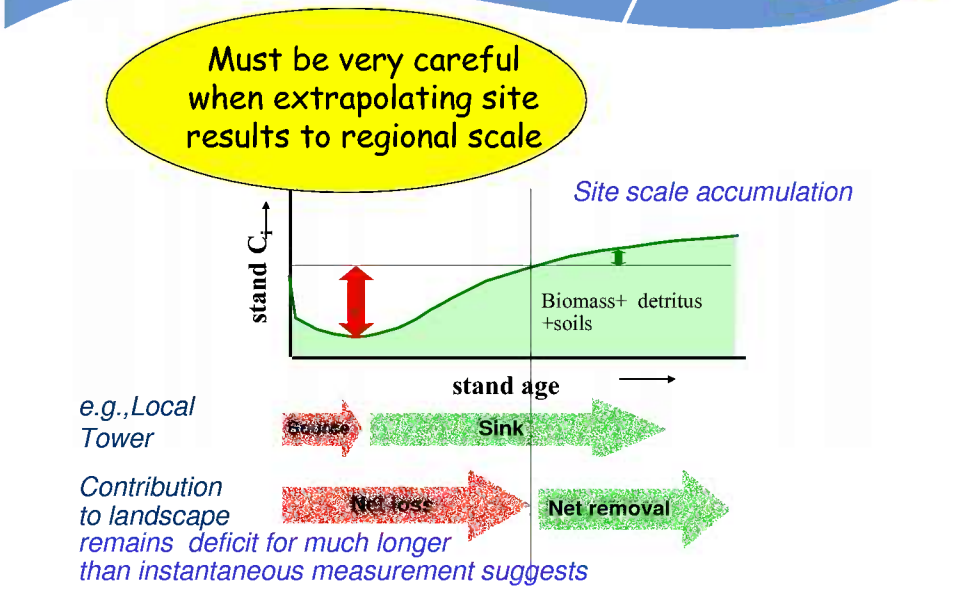
2. *Changes in demographics* *(age distribution) due to change in mortality (LUC or natural disturbances)*

- *At landscape or regional scale, age distribution (historical pattern of mortality)*



Over time, if changes in mortality rates cause:

- *Shift of average age to right C increases (i.e., landscape becomes a **sink**)*
- *Age shift to left, C decreases (i.e. landscape becomes a **source**)*



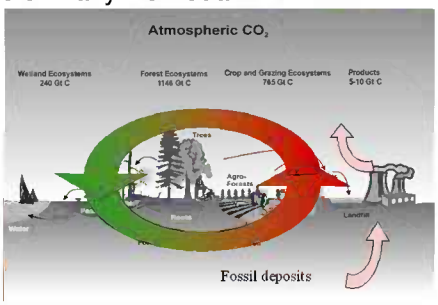
Systems Perspective

At any scale, net flux is complex balance of many individual time varying fluxes each having different control factors

Two basic approaches to carbon balance:

1) Flux estimates
2) Pool (stock) change

Equivalent results (conservation of mass) if and only if all significant fluxes (1), and all significant stock changes (2) are accounted.

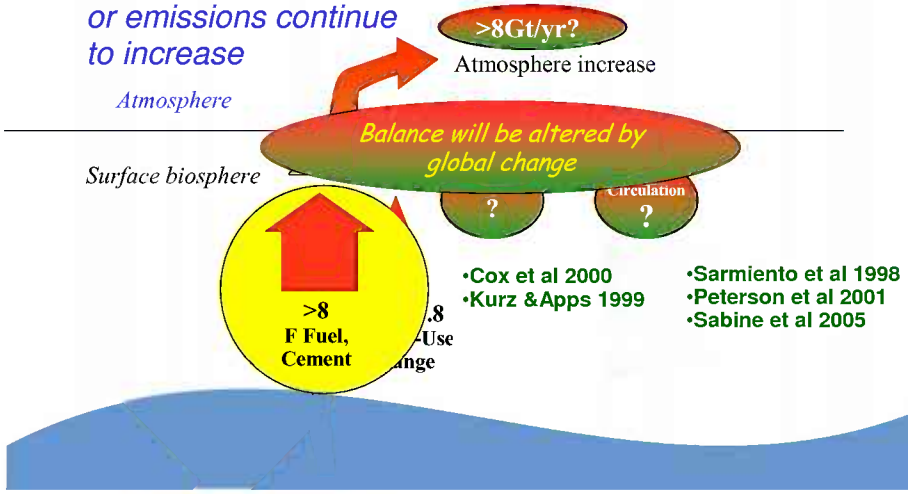


Carbon balance at a global scale

e.g., Houghton (2003)

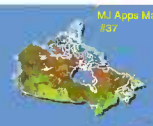
Systems Perspective

Important for predicting future atmospheric C balances if some of the present feedbacks fail ... or emissions continue to increase

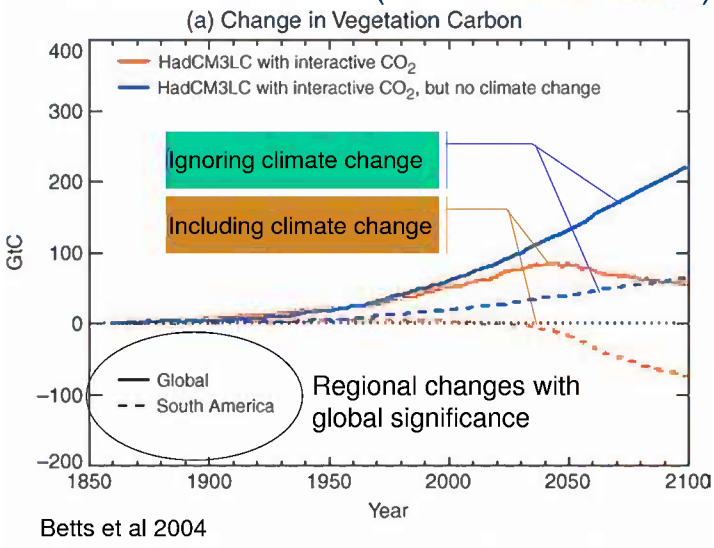


- Cox et al 2000
- Kurz & Apps 1999
- Sarmiento et al 1998
- Peterson et al 2001
- Sabine et al 2005

Example of Change in Balance of Mechanisms



Modelled C feedbacks (dieback in Amazon)

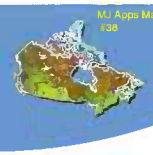


Uptake

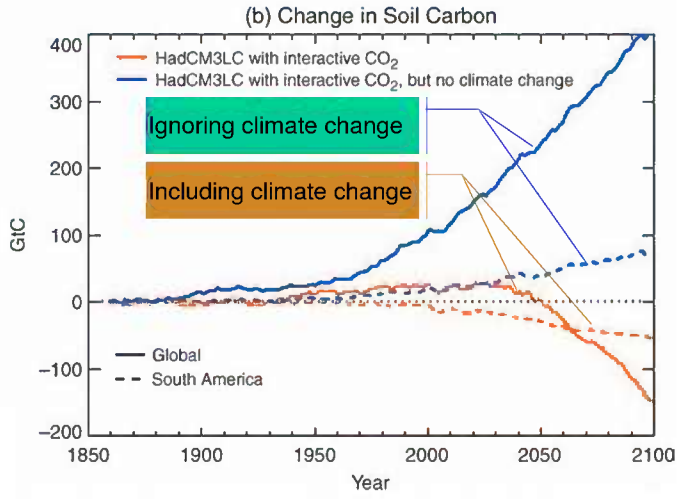
Release

Betts et al 2004

Example of Change in Balance of Mechanisms



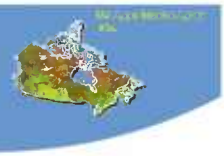
Even larger changes simulated for soils



Uptake

Release

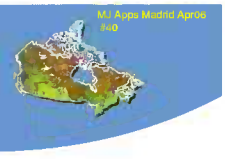
Change in Balance of Mechanisms



Caveats

- The 11 new coupled Climate-Carbon Cycle models all show similar behavior, but the magnitude of the feedback differs widely between models (feedback amplification factors 4% - 44%).
- Impact depends not just on C_{atm} but also depends on the rate of increase of C_{atm} (and T → vegetation response)
- Ocean sink will decrease even in absence of climate feedback due to changes in pH
- Biggest uncertainties are in changes in vegetation and soils (both in response to climate change and to mitigation efforts)

Example of Shift in Demographics

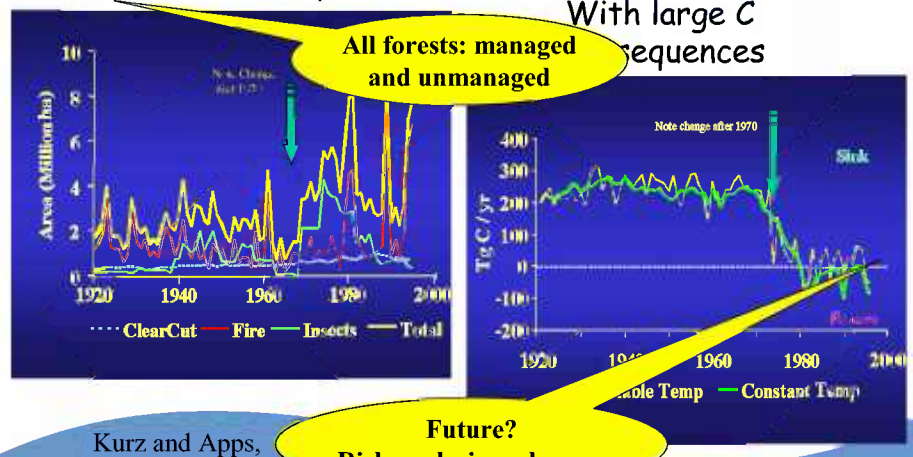


natural

Changing disturbance regime in Canadian forests over last 50 years

With large C sequences

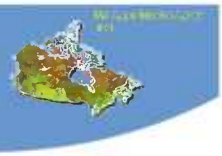
All forests: managed and unmanaged



Kurz and Apps, Ecol. Appl. 1999

Future? Risk analysis underway

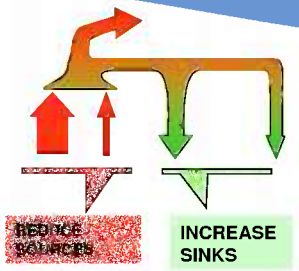
Shift in Demographics



Reports of similar landscape-scale phenomena (i.e., changes in disturbance regime that induce decrease in sinks or increase in sources) are appearing in the literature:

- Other fire prone areas
- Severe windstorms in Europe (and elsewhere)
- Severe dieback from episodic drought
- Increased/new insect outbreaks (Canada, Alaska, …)
- Large scale floods
- …

LULUCF Mitigation

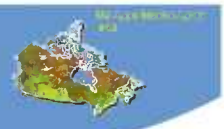


Clearly both human sources and biological sinks must be managed. Land management (LULUCF) can contribute to both:

- Reduce Sources
- Increase Sinks

four general strategies:

Four LULUCF Mitigation Strategies

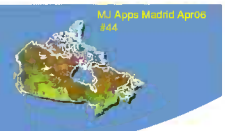


1A	Increase **areas** of high C stocks *(e.g., new forests)*	↑	∫	∫
B	Maintain areas of high C stocks *(e.g., prevent deforestation, LUC)*	↓	∫	∫
2A	Increase **site-level** C density *(e.g., intensive mgmnt, fertilize)*	↑	∫	∫
B	Maintain site-level C density *(e.g., avoid degradation)*	↓	∫	∫
3A	Increase **land-scape** scale C stocks *(e.g., SFM, agriculture, …)*	↑	∫	∫
B	Maintain land-scape scale C stocks *(e.g., suppress disturbances)*	↓	∫	∫
4A	Increase **off-site** C in products *(but must also meet 1B, 2B and 3B)*	↑	∫	∫
B	Increase bioenergy and substitution *(but must also meet 1B, 2B and 3B)*	↓	∫	∫

Type/Magnitude
Enhance sink ↑
Reduce source ↓

Timing dC/dT
Delayed ∫
Immediate ∫
Sustained or repeatable ∫

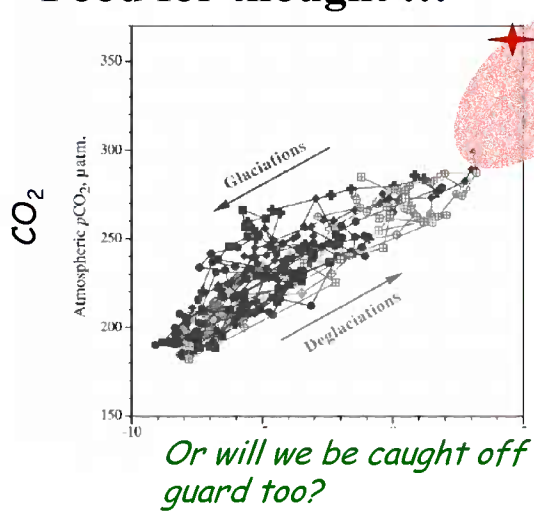
Cost timing $(T)
Delayed ∫
One time ∫
ongoing ∫



Conclusions

- Biological sources and sinks are causally linked - different phases of life history
- Rates and risks for sources *vs* sinks are asymmetric
- Climate change itself poses a significant threat to biological C storage
- Mitigation via LULUCF:
  - both sink enhancement and source avoidance
  - Some are short-term, one-off; others are long-term or repeatable
- Mitigation Potential:
  - Locations depleted of C:- manage as sinks
  - Locations high in C:- manage for source avoidance
  - Largest opportunities lie in source avoidance

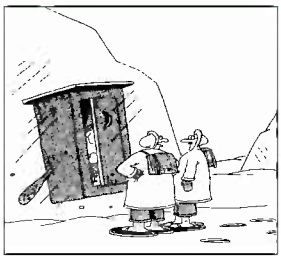
Food for thought …



Today

Future?

Can we manage our activities so that this future will be one that humans would choose?



Or will we be caught off guard too?

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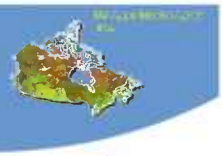

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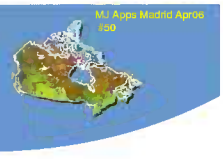
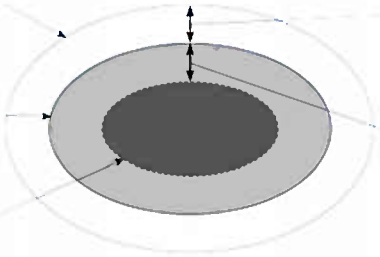


Distinguishing Technical, Economic, and Policy Potentials

Technical Potential
(expressed in million tons of carbon, regardless of carbon price)

Economic Potential
(expressed in tons available, at given carbon price)

Policy Potential
(expressed in eligible tons available, at given carbon price)

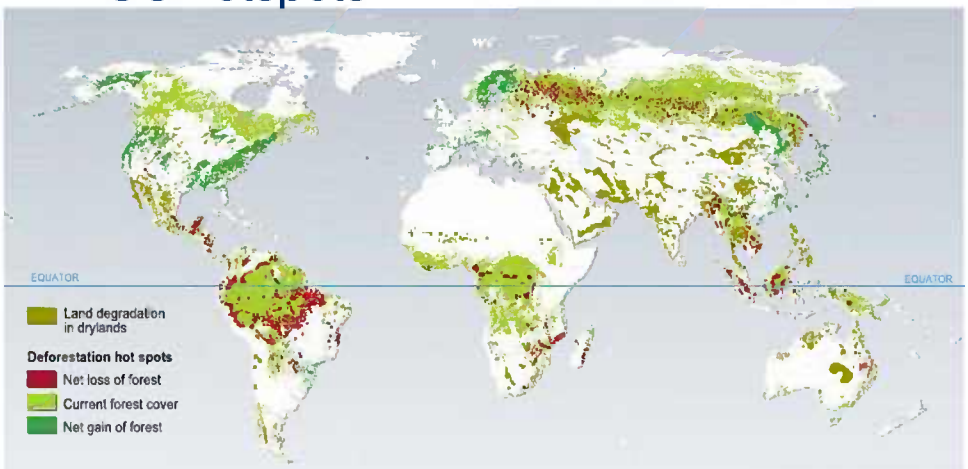


Difference between **technical** and **economic** potential is equal to sequestration opportunities that are not cost-effective to implement at current and future carbon prices

Difference between **economic** and **policy** potential is equal to sequestration opportunities that do not meet eligibility criteria set by policy (e.g., geographic restrictions)

SOURCE: UCS (2004)

LUC hotspots



Areas undergoing high rates of land cover change between 1980 and 2000

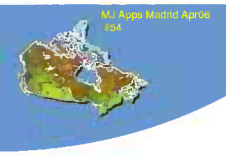
Source: Millennium Ecosystem Assessment

Summary: Science issues and challenges

Quantitative understanding the spatial and temporal dynamics of the perturbed carbon cycle:

- Reconciling top-down and bottom-up estimates of the global carbon budget
- Understanding the mechanisms that control the major fluxes (***anthropogenic*** *and* ***biospheric***) making up the budget
- Predicting how the budget will change over time
- Observation and measurement challenges posed by the above needs

The way forward?



'Better' *regional* carbon budgets

- Data, comprehensive (processes, sectors, pools), spatial representation, dynamic

that can be used

- to **constrain** and **augment** global budgets
- to **inform** decision makers at regional scales
- to **enable** implementation of carbon management strategies
- to **monitor** progress at relevant scales and **facilitate** adaptive management


Global
Carbon
Project
Think globally,
analyze locally