Future of the North American Carbon Cycle

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https://doi.org/10.7930/SOCCR2.2018.Ch19
Globally - Land & oceans vital for regulating atmospheric CO₂

Sources = Sinks

<table>
<thead>
<tr>
<th>Sources</th>
<th>Sinks</th>
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<tbody>
<tr>
<td>88%</td>
<td>46%</td>
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<tr>
<td>9.4 ± 0.5 PgC/yr</td>
<td>4.7 ± 0.1 PgC/yr</td>
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<tr>
<td>12%</td>
<td>30%</td>
</tr>
<tr>
<td>1.3 ± 0.7 PgC/yr</td>
<td>3.0 ± 0.8 PgC/yr</td>
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<tr>
<td>24%</td>
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<tr>
<td>2.4 ± 0.5 PgC/yr</td>
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</tbody>
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Adapted from [Global Carbon Budget 2016](https://www.globalcarbonproject.org/publications/global-carbon-budget-2016)

Numbers based on Chapter 1, SOCCR-2; Table 1.1 (2007-2016 avg)
Major Components of the NA Carbon Cycle

Values in Tg C

From Chapter 2 of SOCCR-2, Hayes et al.
Major Components of the NA Carbon Cycle

Land and coastal oceans currently a net sink of carbon
By taking up atmospheric CO$_2$, land and oceans play a critical role in slowing the accumulation of carbon in the atmosphere – thereby slowing rate of climate warming.

Will the land and oceans continue to provide this service into the future?

Or, will the ocean and land carbon sinks decrease (or switch to source) under changing environmental conditions?
Future of the North American Carbon Cycle?

Atmosphere

Fossil Fuel Emissions
Product Emissions

Net Ecosystem Flux

Gas Emissions
Uptake
Outgassing

Tidal Wetlands
Sediment
Lateral Flux

Inland Waters
Lateral Flux

Estuaries
Sediment
Lateral Flux

Coastal Ocean
Transfer to Open Ocean

Wood Harvest

Fossil Fuels
Products
Wood

Land Ecosystems
Arctic/Boreal Forests 14
Urban Trees 27
Agricultural Soils 15

1,009**
Predicting future carbon cycle changes

Requires ability to estimate response of land and aquatic systems to numerous, often competing, drivers.
This talk – review current understanding of potential changes in NA carbon cycle.

- What are major **drivers** of future change?
- What can we say about land and coastal ocean **response** to these drivers?
- What are major knowledge **gaps**?
• **What are major drivers of future change?**
• What can we say about land and coastal ocean response to these drivers?
• What are major knowledge gaps?
Drivers – Fossil Fuel Emissions (↑ in atmospheric CO₂)

Emissions from fossil fuel burning are a source of carbon to atmosphere, and will continue to be a source into the future.

By 2040, projections suggest total NA fossil fuel C emissions could ↓ by 12.8% or ↑ by 3% compared to 2015 levels.

Uncertainties → future energy policies, technologies, prices, economic growth, demand, and other things that are difficult-to-predict.
- Human-driven changes in land-cover & land-use will continue to be a key driver of carbon cycle changes into the future.
- Globally, land use change is projected to add carbon to the atmosphere.
- But in U.S., future land-use activities are projected to take carbon from atmosphere through increased carbon uptake of \(\sim 4 \text{ PgC by 2030}\) by terrestrial ecosystems.
Drivers – Climate (Temperature)

Increase by 2.5 deg F in coming decades

Increase by 6-12 deg F by end of century

From Climate Science Special Report, 2018
Drivers – Climate (Precipitation)

High latitudes wetter; subtropical regions drier
Drivers – Climate (Extremes)

Hot days

- From Climate Science Special Report, 2018

Cold days

- Extreme precip. events

- Change (%):
  - 0-4
  - 5-9
  - 10-14
  - 15+

- From Climate Science Special Report, 2018
• What are major drivers of future change?
• What can we say about land and coastal ocean response to these drivers?
• What are major knowledge gaps?
Land carbon cycle sensitive to:

- Atmospheric composition (e.g., $CO_2$)
- Temperature and precipitation
- Disturbances (e.g., fire, disease)
- Land-use and land-cover change
- Nutrient availability
Changes – Land Carbon

Response to rising atmospheric CO$_2$

a. Regional carbon-concentration feedback

- Land C uptake projected to ↑ with ↑ atmospheric CO$_2$
- Magnitude of response uncertain:
  - Depends on age of trees
  - Nutrients will likely constrain response
  - Uncertain impact on soil carbon stocks

From IPCC, 2013
Changes – Land Carbon

Response to climate warming

b. Regional carbon-climate feedback

- Carbon losses due to climate warming projected to partially offset carbon gains caused by $\uparrow$ atmospheric CO$_2$.

- Magnitude of response uncertain:
  - Heat stress and respiration projected to $\downarrow$ land C uptake in temperate NA
  - Lengthened growing season at high northern latitudes could $\uparrow$ land C uptake

From IPCC, 2013
Globally, soil store 1,500 to 2,400 Pg C (more than twice C in atmosphere)

Warming in the Northern high-latitudes (Alaska and Canada) is making carbon stored in permafrost soils vulnerable to release to the atmosphere

These losses could shift region from net sink to net source of carbon.

From Crowther et al., 2016
Global-scale – series of Representative Concentration Pathways (RCPs) created to account for different possible futures

Low emissions
Stabilization scenarios
High emissions

(a)

(b) Fossil Fuel Emissions

Land-Use Emissions

Gt C per Year

2000 2020 2040 2060 2080 2100

Solar/Wind/Geothermal
Hydro
Bioenergy
Nuclear
Natural Gas
Oil
Coal
By 2050, models project a slight decrease to a doubling of the current land C sink strength.

By 2100, strength of the NA net land C sink projected to either remain near current levels or decline significantly.

Uncertainty comes from combined and uncertain effects of rising CO$_2$, climate change, emission scenarios and land-use management.
Globally, coastal oceans account for 41% of ocean area.

NA makes up 10% of global coasts and includes rivers, estuaries, tidal wetlands, and continental shelf.

From Chapter 16, SOCCR-2
Changes – Coastal Ocean

Response to rising atmospheric CO₂

The pH of ocean waters boarding NA are projected to decrease by 0.4 to 0.5 pH units by 2100 (under highest emission scenarios).

Warmer and more CO₂ enriched waters are expected to take up less additional CO₂ and have reduced buffering capacity (due to ocean acidification).

↑ atmospheric CO₂ is projected to ↑ coastal ocean carbon uptake.

From NOAA

From Chapter 16, SOCCR-2
Changes – Coastal Ocean

Response to climate warming

- Warming climate is projected to **reduce** coastal ocean carbon uptake in most regions of NA.
  - Increase stratification
  - Slow ocean circulation
  - But impacts are regional and uncertain

- Warming and changes in precipitation may **impact** river carbon fluxes
  - Extreme rainfall events could shift timing of carbon delivery to coastal oceans
Since 1870, NA coastal oceans have taken up 2.6 to 3.4 Pg C from atmosphere.

Under highest emission scenarios, projected to take up an additional 10 to 12 Pg C by 2050.

And another 17 to 26 Pg C in between 2050 and 2100.

Uncertainties due to climate warming, changing circulation, ocean acidification, human pressures, and land processes
Primary contributors to carbon cycle change over North America are, and will continue to be, emissions from fossil fuel combustion, changes in land cover and land use, and changing climate conditions.

Projections suggest that natural carbon sinks of North America (land, coastal ocean systems) are diminishing in strength and many are at risk into the future.

Accelerated warming in the Northern high-latitudes (Alaska and Canada) is making large stores of carbon in permafrost soils vulnerable to release to the atmosphere by the end of the century.
• What are major drivers of future change?
• What can we say about land and coastal ocean response to these drivers?
• What are major knowledge gaps?
Knowledge Gaps – CO$_2$ Fertilization

- Crucial for projecting future changes in carbon cycle.
- Lack of understanding about carbon-nitrogen coupling and its controls on CO$_2$ fertilization response.
- Models agree on direction, but not on magnitude of response.

From IPCC, 2013
By 2100, soil carbon losses from the northern high-latitudes will determine the trajectory of the carbon cycle.

Vegetation may help regulate / offset the net response of this region to warming.

Knowledge gaps →
- Area and depth of vulnerable permafrost
- Speed of carbon release from thawing soils
- Form of carbon release
Knowledge Gaps – Disturbance, Drought, Land-Use Change

- **Disturbance (fire, insect outbreaks, other)** - largely expected to increase, but timing, magnitude and impacts uncertain.

- **Droughts** – expected to increase in severity, area, and duration. Vegetation response to future drought conditions unclear, particularly long-term impacts.

- **Land-use and land-cover changes** – challenging to predict, both in terms of ecosystem changes and because of social, economic, and climate impacts on land use.
Knowledge Gaps – Models

Key sources of uncertainty in models –

- Model uncertainty – structure and parameterization
- Scenario uncertainty – input data and forcing scenarios

From Bonan and Doney, 2018
Acknowledgements

- David J. P. Moore, University of Arizona;
- Sara Ohrel, U.S. Environmental Protection Agency;
- Tristram O. West, DOE Office of Science;
- Benjamin Poulter, NASA Goddard Space Flight Center;
- Anthony P. Walker, Oak Ridge National Laboratory;
- John Dunne, NOAA Geophysical Fluid Dynamics Laboratory;
- Sarah R. Cooley, Ocean Conservancy;
- Anna M. Michalak, CIS and Stanford University;
- Maria Tzortziou, City University of New York;
- Lori Bruhwiler, NOAA Earth System Research Laboratory;
- Adam Rosenblatt, University of North Florida;
- Yiqi Luo, Northern Arizona University;
- Peter J. Marcotullio, City University of New York;
- Joellen Russell, University of Arizona
- Melanie Mayes, Oak Ridge National Lab;
- Tara Hudiburg, University of Idaho;
- Elisabeth Larson, NASA Goddard Space Flight Center, Science Systems and Applications Inc.;
- John Schade, National Science Foundation;
- Karina V.R. Schäfer, Rutgers University;
- Nancy Cavallaro, USDA National Institute of Food and Agriculture;
- Zhiliang Zhu, U.S. Geological Survey;
- Gyami Shrestha, U.S. Carbon Cycle Science Program Office Director; UCAR Cooperative Programs for the Advancement of Earth System Science
- Richard Birdsey, Woods Hole Research Center
- Raymond G. Najjar, The Pennsylvania State University
- Sasha C. Reed, U.S. Geological Survey
- Paty Romero-Lankao, National Center for Atmospheric Research (currently at National Renewable Energy Laboratory)
Questions?

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