Late Quaternary changes in the terrestrial biosphere: causes and consequences

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NGEN03
2014
The global carbon cycle

Marshak, 2001
Direct measurements of atmospheric CO₂ concentration

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/)
Changes in greenhouse gas concentrations over the past 1000 years
Changes in CO$_2$ concentration over the past 45,000 years

Atmospheric CO$_2$ Concentration
Last Glacial Maximum to present

Adapted from: http://www.climate.unibe.ch/gallery_co2.html
Changes in the concentration of \( \text{CO}_2 \) and \( \text{CH}_4 \) over the past 420,000 years and projections for the future
Earth’s climate system

CAUSES (external forcing)
- Changes in plate tectonics
- Changes in Earth's orbit
- Changes in Sun's strength

CLIMATE SYSTEM (internal interactions)
- Atmosphere
- Vegetation
- Ice
- Land surface
- Ocean

CLIMATE VARIATIONS (internal responses)
- Changes in Atmosphere
- Changes in Ice
- Changes in vegetation
- Changes in Ocean
- Changes in land surface

Ruddiman, 2001
Orbital effects on insolation and climate

Marshak, 2001
Phasing of changes in the climate system and carbon cycle over the past 420,000 years.
The terrestrial biosphere

- Two components: vegetation and soils
- Regulates the fluxes of energy, water and aerosols between Earth’s surface and the atmosphere
- Central to the biogeochemistry of the planet (especially C and N cycles)
- Involved in biogeochemical and biophysical feedbacks
- Important and complex component of the climate system
Why look into the past?

• To assess how the terrestrial biosphere will respond to future climate change, we need to understand how it has responded and interacted in the past
• Information on biospheric responses on decadal and longer timescales
• Information on biosphere dynamics associated with large climatic changes and in absence of anthropogenic influences
• Data to test process-based models
Biogeochemical roles of the terrestrial biosphere

• May contribute to glacial-interglacial \( \text{CO}_2 \) changes (mainly caused by oceanic processes)
• Major control of glacial-interglacial \( \text{CH}_4 \) changes (wetlands: distribution and hydrological status)
• Important cause of Holocene \( \text{CO}_2 \) and \( \text{CH}_4 \) variations (vegetation: distribution and net primary production; soils and wetlands: hydrological status)
• Important for global climatic conditions
Biophysical roles of the terrestrial biosphere

- Vegetation influence on land-surface albedo
- Vegetation influence on water availability
- Vegetation influence on surface roughness
- Important for climatic conditions on local, regional and global scales
Examples of positive feedbacks involving vegetation

Ruddiman, 2001
Biological responses to climatic variations, and methods to study them

- Changes in productivity/growth or death: dendroclimatology (tree rings)
- Changes in population size: palaeoecology (microfossils, macrofossils and megafossils)
- Changes in community composition: palaeoecology
- Species migration: palaeoecology
- Changes through evolution
- Extinction
Dendroclimatology

Ruddiman, 2001
Palaeoecology: examples of studied organisms

- Pollen
- Diatoms
- Plant macrofossils
- Chironomids
Changes in population size and community composition

Spruce
Birch
Aspen
Juniper
Alder
Willow
Bog myrtle
Mugwort/Wormwood
Grasses
Species migration

Frequency of oak (*Quercus*) pollen

- 13 ka
- 11 ka
- 9 ka
- 7 ka

Frequency of lime (*Tilia*) pollen

- 10 ka
- 9 ka
- 8 ka
- 6 ka

Bennett (1997), after Huntley & Birks (1983)
Species migration

2000 years ago

Spruce (Picea)

©SNA

1000 years ago

Beech (Fagus)

©SNA

present

©SNA
## Extinction

### Modern Distribution

<table>
<thead>
<tr>
<th>Genus</th>
<th>Range of Genera in Quaternary Interglacials of N.W. Europe</th>
<th>Modern Distribution</th>
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Extinction

Guthrie (2006)

Ruddiman, 2001

Johnson (2009)
Capacity of the terrestrial biosphere to keep pace with climate change

• Varies across temporal scales
• Short-term (years) climatic fluctuations often invoke only minor or no responses (if limited in amplitude; in long-lived organisms)
• Intermediate (decades-centuries) rates of climate change cause complex non-equilibrium responses (some parts of the system respond immediately, others lag behind)
• Slow (millennia and longer) variations in climate: dynamic equilibrium (terrestrial biosphere keeps pace with climate change); results in biospheric feedbacks on climate change
Biospheric responses to glacial-interglacial cycles

- Species respond individualistically and in dynamic equilibrium with climate (migration)
- Repeated formation and break-up of biomes
- Specialization of taxa (migrational strategies, adaption)
- Elimination of species that are unable to adapt, unable to migrate, or rare (extinction)
- Limited speciation (too short time within cycles for directional adaptive evolution?)
- Less dramatic biogeographic shifts in mountain areas (suitable conditions available locally)
- Changes in carbon storage by vegetation and soils
Vegetation responses on glacial-interglacial timescales

Ruddiman, 2001
Environmental conditions and biomes during the last glacial maximum

Hewitt (2000)
European vegetation at present and during the last glacial maximum

A Modern vegetation
- Ice
- Tundra and mountain
- Boreal forest
- Deciduous and conifer forest
- Mediterranean scrub
- Prairie-steppe

B Glacial vegetation

Ruddiman (2001)
The glacial-interglacial cycle of ecosystem development
CO$_2$, temperature and CH$_4$ over the past four glacial-interglacial cycles

4 glacial cycles recorded in the Vostok ice core

Glacial-interglacial changes in CH$_4$ and low-latitude insolation

Hypotheses to explain CH$_4$ changes during glacial-interglacial cycles

• Orbitally forced changes in low-latitude monsoon strength resulting in variable distribution and status (wet/dry) of wetlands

• Orbitally forced changes in high-latitude temperatures resulting in variable CH$_4$ production in wetlands

• Orbitally forced changes in high-latitude temperatures resulting in melting/freezing of permafrost in wetlands and variable CH$_4$ emissions

• Methane hydrates?
Biospheric responses to climate changes on millennial timescales

• Regional shifts in species distributions
• Changes in community composition
• Changes in carbon storage by vegetation and soils
European vegetation development since the last glacial maximum

Distribution of "vegetation units" based on pollen data

Huntley (1990)
Millennial-scale CH$_4$ variations during the last glacial period and deglaciation

Ruddiman, 2001
Millennial-scale changes in CH$_4$ during the Holocene

Raynaud et al. (2000)
Peat initiation in circumarctic peatlands

(MacDonald et al., 2006)
Timing of Holocene peatland establishment and CH$_4$ concentrations

MacDonald et al. (2006)
Long-term Holocene increases in CO$_2$ and CH$_4$: natural or anthropogenic?

Ruddiman, 2003
Millennial-scale CO$_2$ and carbon cycle changes during the Holocene

Elsig et al. (2009)
Biospheric responses to climate changes on sub-millennial timescales

- Reproduction, growth and mortality of individual plants and species
- Changes in community composition
- Changes in carbon storage by vegetation and soils
Temperature-related growth changes on sub-millennial timescales

Siberian larch

Mongolian larch

Ruddiman, 2001
Changes in forest composition on sub-millennial timescales

Tinner & Lotter, 2001
Sub-millennial CH$_4$ changes during the Holocene

Spahni et al., 2003
Sub-millennial CH$_4$ changes during the Holocene

Ferretti et al., 2005
Sub-millennial CO$_2$ changes during the Holocene

Reconstructed CO$_2$ (ice cores)

Reconstructed Northern Hemisphere temperature

Masson-Delmotte et al. (2013), IPCC AR5, WGI
The terrestrial biosphere: concluding remarks

- Responds to climatic changes on a variety of timescales
- Influences other parts of the climate system through biogeochemical and biophysical feedbacks
- Influenced directly by atmospheric CO$_2$ concentration (net primary production, water-use efficiency)
- Important and complex component of the climate system