Vulnerabilities and Thresholds in the Carbon-Climate-Human System

Mike Raupach, Pep Canadell

Global Carbon Project, Earth System Science Partnership
CSIRO Earth Observation Centre
Aspiration and Outline

Aspiration of this talk
◆ Survey vulnerabilities in climate-carbon and carbon-climate-human system
◆ Seek common patterns
◆ Seek consistent measures of vulnerability
◆ Seek a Complex Adaptive System (CAS) perspective on vulnerability

Outline
• Defining vulnerability
• Vulnerability and climate
• Vulnerability and the carbon cycle
• Vulnerability and humans
• Synthesis
“Vulnerability” is a richly loaded word

Climate

- “Human impacts on the environment are now large enough that the climate system itself is vulnerable to human interference”

Carbon

- “Land and ocean carbon pools are vulnerable to increased CO₂ release as the climate warms, thus accelerating the warming”

Humans

- "Poor nations are the most vulnerable to climate change"
Defining vulnerability

- **Definition (Turner et al. 2003)**

  “Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor.”

- Thus we need to:
  1. Identify the system or system component
  2. Identify the forcing (hazard) and response (harm)
  3. Define a measure of "degree to which system is likely to experience harm"
  4. Apply this measure, act on result
Carbon-climate-human interactions

1. Biophysical feedbacks
2. Forcing
3. Impacts
4. Response
Vulnerability and Climate

Outline

- Defining vulnerability
- Vulnerability and climate
- Vulnerability and the carbon cycle
- Vulnerability and humans
- Synthesis
Atmospheric CO$_2$: past and future

- Last 420,000 years: Vostok ice core record (blue)
- Last 100 years: Contemporary record (red)
- Next 100 years: IPCC BAU scenario (red)
Climate thresholds

Ice-age temperature records:

- Vostok oscillations
  - Period around 100 ky

- Dansgaard-Oescher (DO) oscillations
  - Variable period, typically a few ky
Simplified climate model for DO oscillations *(Rial 2005)*

- Ice-core temperatures in Greenland
The Milenkovich cycles

**Eccentricity**
41,000 years

**Tilt or obliquity**
41,000 years

**Precession of the equinoxes**
23,000 years
Thresholds in the climate system

- **Astable oscillator**
  
  - Mechanism for generating a sawtooth waveform
  
  - No external forcing required to trigger threshold event
Thresholds in the climate system

- Frequency modulation of astable oscillator

- External (Milenkovich) forcing changes the frequency of threshold events
The Saltzmann nonlinear thermal oscillator

ICE AGE ATMOSPHERE

$L(t)$

$0$

$T(t)$

OCEAN

$\theta(t)$
Self-sustained relaxation oscillation of the Saltzmann nonlinear thermal oscillator
Simplified climate model for DO oscillations (Rial 2005)
Vulnerability and climate

- The planetary climate of Earth is dynamic: abrupt changes are the norm.
- Changes typically have a threshold-like character (fast warming, slow cooling).
- Thresholds are driven by a combination of self-organisation and external forcing:
  - Self-organisation (endogenous drivers):
    - Ice, oceans, CO2, dust, plants
    - Vulcanism-carbonate cycle
    - Continental drift
  - External forcing (exogenous drivers):
    - Orbital forcing
    - Meteorites
- Climate thresholds imply **vulnerabilities** for ecosystems and the biosphere.
- Within a wide envelope of change, the Earth System is remarkably **resilient**.
Vulnerability and the carbon cycle

- Defining vulnerability
- Vulnerability and climate
- Vulnerability and the carbon cycle
- Vulnerability and humans
- Synthesis
The current carbon cycle (Sabine et al 2004)

Vulnerability of terrestrial biogenic carbon

The current carbon cycle: detail for land (Sabine et al 2004)
Vulnerable land and ocean carbon pools, 2000-2100

Gruber et al. (2004, SCOPE-GCP)
Drought and warming => loss of vegetation

- **Australian continent:** AVHRR-NDVI anomaly, 1981-2003

- Current version (Oct 2003) uses EOC "B-PAL" archive of AVHRR data

- 5 km, 8-11 day composites

- Still to incorporate:
  - Atmos correction
  - BRDF correction
  - 1-km data
Drought and warming => loss of vegetation C


Peter Briggs, Edward King, Jenny Lovell, Susan Campbell, Michael Raupach
Vulnerability of fossil carbon pools

The current carbon cycle: detail for land (Sabine et al 2004)
### Trends in national carbon emissions (1950 to 2000)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>1950 Rank</th>
<th>2000 Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>USA</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>China</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Russia (FSU=2)</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Japan</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>India</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Germany</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>UK</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>Canada</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>Italy</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>South Korea</td>
<td>57</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>Mexico</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>Saudi Arabia</td>
<td>47</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>France</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>Australia</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>Ukraine (FSU=2)</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>South Africa</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>Iran</td>
<td>28</td>
<td>17</td>
</tr>
<tr>
<td>18</td>
<td>Brazil</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td>Poland</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td>Spain</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

Vulnerability and human systems

Outline

• Defining vulnerability

• Vulnerability and climate

• Vulnerability and the carbon cycle

• Vulnerability and humans

• Synthesis
Food supplies in less developed countries are more badly affected by climate change than those in developed countries.
Water

- Effects of climate change on water supply are variable, but tend to be more severe in less developed countries (Africa, Central America) than in developed countries.

- Population changes will amplify this imbalance.

Vörösmarty et al 2000, Science
Vulnerability of networks: individuals matter
Influence network for development of Montreal Protocol

Canan & Reichman 2002,
*Ozone Connections: Expert Networks in Global Environmental Governance*
Synthesis

Outline

• Defining vulnerability

• Vulnerability and climate

• Vulnerability and the carbon cycle

• Vulnerability and humans

• Synthesis
Quantifying and coping with vulnerability

- Quantifying vulnerability
  - Vulnerability = \([\text{Cost of harm}] \times \text{Prob(harm)}\)
    \(= \text{[Cost of harm]} \times \text{Prob(harm, given hazard)} \times \text{Prob(hazard)}\)

- Coping with vulnerability: reduce vulnerability by
  - Reducing probability of harm, by reducing the stress (mitigation)
  - Reducing cost of harm, by reducing the impact (adaptation)

- The problem of transferred harm:
  - Spatial transfer: In climate change, the main generators of stress are not the same people as those experiencing most of the harm
  - Temporal transfer: There is a time delay between the stress and the harm
  - \(\Rightarrow\) Low incentives for mitigation
Attributes defining a Complex Adaptive System (CAS)
- Hierarchy: system consists of components interacting by (fairly) simple rules
- Self-organisation: internally generated, not externally imposed
- Evolutionary emergence: organised system behaviour evolves in time, allowing complexity (information content) to increase
- Adaptive capacity: system has the capability to survive
  - its own autonomous cycles and thresholds,
  - changes in external conditions

An evolving CAS is both resilient and vulnerable

Dynamics inducing vulnerability in a CAS:
- thresholds, regime shifts, bifurcations, limit cycles, chaos

These system-wide phenomena can lead to:
- system collapse (without or with recovery)
- collapse of a component (without or with recovery)
Human-biosphere interaction as a dynamical system
A two-equation model

- State variables:
  \[ B(t) = \text{biomass} \]
  \[ H(t) = \text{human population} \]

- Equations:

\[
\frac{dB}{dt} = P - kB - E ; \quad \frac{dH}{dt} = g \left( E - mH \right)
\]

- Model for extraction of biomass by humans:
  \[ E = cBH \]

  - more humans extract more biospheric resource
  - each human extracts more as \( B \) increases (\( B \) is surrogate for quality of life)
Human-biosphere interaction as a dynamical system
Trajectories on a \((B,H)\) plane with random climate variability in production

Random primary production: log-Markovian, sd = 0.5, varying time scale
Human-biosphere interaction as a dynamical system

Trajectories on a \((B,H)\) plane for 6 scenarios

- **Eden**
  - \(B = \text{biomass}\)
  - \(H = \text{humans}\)

- **Occupy**
  - \(B = \text{biomass}\)

- **Disaster**
  - \(B = \text{biomass}\)

- **Grow**
  - \(B = \text{biomass}\)

- **Subsist**
  - \(B = \text{biomass}\)

- **Exploit**
  - \(B = \text{biomass}\)