Climate Change on Agriculture, Water and Environment

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Outline

► Climate Change: Causes
► Climate Change and Agriculture: Impacts
► Climate Change on Water: Case studies in India and China Using the SWAT model
► Climate Change and Agriculture: Adaptation and Mitigation
► Summary

In 2007, IPCC synthesized knowledge on causes and effects of anthropogenic climate change

![Glacial-Interglacial Ice Core Data](source: Technical Summary IPCC Working Group I [Rahman et al., 2007])

But the efforts and insights started much earlier...

► Svante Arrhenius (1859 – 1927)
  - Physical Chemist
  - PhD thesis on electrolytic conductivity
  - Developed Arrhenius equation
  - Proposed greenhouse gas law
    - "If the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression"

► C. David Keeling (1928 - 2005)
  - Chemist
  - Developed instrument to measure [CO₂] in atmospheric samples
  - Established Mauna Loa Observatory in 1958
  - Demonstrated the progressive buildup of [CO₂] in the atmosphere

But, what is a “greenhouse gas” anyway?

- Nitrogen, O₂, and Ar make up for 99% of the atmosphere but are not greenhouse gases
- Water vapor, CO₂, CH₄, and N₂O are greenhouse gases
- A greenhouse gas absorbs infrared radiation because of their dipole moment
  - This dipole moment creates molecular vibration and bending and as a result the molecule absorbs infrared radiation
  - Collisions transfer energy to heat the surrounding gas

![The N₂O molecule](http://www.ucar.edu/learn/131.htm)

How do we compare greenhouse gas?

Two definitions and a formula

► Radiative Forcing: Change in net irradiance (W m⁻²) at the tropopause after allowing stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures held at their unperturbed values
  - A positive value warms the system while a negative value cools it

Global Warming Potential (GWP):
Cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now, expressed relative to CO₂

\[
GWP_{N₂O} = \frac{N₂O(Wm^{-2}g^{-1}(100y)^{-1})}{CO₂(Wm^{-2}g^{-1}(100y)^{-1})}
\]

- The GWP for N₂O varies according to the time considered:
  - For 20 years: 310 gN₂O (gCO₂)⁻¹
  - For 100 years: 298 gN₂O (gCO₂)⁻¹
Comparing the power of greenhouse gases
4th IPCC Assessment Report, WG I, Ch. 2

- Human activities result in emissions of four principal greenhouse gases: CO₂, CH₄, N₂O and the halocarbons (a group of gases F₃, C₁ and Br)
- Atmospheric concentrations of long-lived greenhouse gases have been increasing over the last 2,000 years, especially since 1750—the beginning of the industrial era

<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentrations and Δa (ppm)</th>
<th>Radiative Forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>Δ since 1990</td>
</tr>
<tr>
<td>CO₂</td>
<td>379</td>
<td>13</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.774</td>
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<tr>
<td>N₂O</td>
<td>0.319</td>
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</tr>
</tbody>
</table>

Factors Determining Climate Change

- Except for the variation in solar radiation, all human activities are connected to a radiative forcing
- Some factors induce warming:
  - CO₂, N₂O, CH₄
- ...while others induce cooling
  - Sulphates (vulcanic eruptions)
  - Some factors are understood better than others

A simple arithmetic sum of radiative forcings is not enough to calculate the total effect (due to the asymmetry in the ranges of uncertainty)

Source: Technical Summary IPCC Working Group I (Solomon et al. 2007)

The rise in continental and global temperatures observed during the past century can only be explained with computer simulations that include the anthropogenic effect

Source: Summary for Policymakers, IPCC (2007)

Relative changes in precipitation during 2090-2099 relative to 1980-1999 in a A1B world

Source: Summary for Policymakers, IPCC (2007)

The projections of temperature changes during the current century relative to 1980-1999 vary with assumptions about the future

- Different scenarios of the future:
  - The B1 scenario has a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development
  - The A1B future shows a world with balanced progress across all resources and technologies from energy supply to end use
  - The A2 scenario contains a world of independently operating, self-reliant nations, continuously increasing population, and regionally oriented economic development

Source: Summary for Policymakers, IPCC (2007)

Global Carbon Cycle (Pg C)
(Based on Schlesinger, 2003)

1 Pg = 10¹⁵ g
= One billion tons

Source: Summary for Policymakers, IPCC (2007)
The challenge of stabilizing CO₂ concentrations...

- Stabilization of greenhouse gas concentrations is the goal of the Framework Convention on Climate Change.
- Stabilization means that global emissions must peak in the decades ahead and then decline indefinitely thereafter.
- Climate change is a long-term, century to millennial problem—with implications for today. It will not be solved with a single treaty, single technology, by a single country, or by a quick fix.

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Filling the Global Carbon Gap...

Energy technologies in the pipeline are not enough!

- Assumed Advances:
  - Fossil Fuels
  - Energy intensity
  - Nuclear
  - Renewables
- Gap Technologies:
  - Improved performance of ref tech.
  - Carbon capture & disposal
  - Adv. fossil
  - H₂ and Adv. Transportation
  - Biotechnologies
- Soils, Bioenergy, adv. Biogas

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The CO₂ fertilization effect...

- The elevated concentration of CO₂ stimulates photosynthesis and reduces stomatal conductance.
- Other effects:
  - Improves water use efficiency
  - Accelerates plant growth
  - Changes the distribution of nutrients
  - Reduces foliar concentration of nitrogen
- Kimball (1983): crop yields should increase 33% when [CO₂] doubles from 330 to 660 ppm.

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Research methods to study [CO₂] effects on plants

- Laboratory chambers
- Glasshouses
- Closed-top field chambers
- Open-top field chambers
- Free-Air Carbon Dioxide Enrichment (FACE)

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General effects of [CO₂] on wheat yield

  - 20 experiments
  - Wheat yield increased 37% when [CO₂] increased from 330 to 660 ppm
  - 113 lab and field experiments with wheat
  - Non-limiting water and nutrients
  - Ambient temperature
  - Wheat yield increased 31% when [CO₂] doubled from 350 to 700 ppm

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http://www.uswcc.ars.usda.gov/pubs/co2face.htm
http://www.env.duke.edu/forest/FACETS.htm
Tropospheric $[O_3]$ has increased due to human activities.

### Ozone and CO$_2$ concentration effects on yield and biomass of wheat in 1991

| Low O$_3$ - Amb. CO$_2$ | 538 | 1513 |
| High O$_3$ - Amb. CO$_2$ | 414 | 1272 |
| Low O$_3$ - Enrich. CO$_2$ | 627 | 1653 |
| High O$_3$ - Enrich. CO$_2$ | 574 | 1559 |

- Rudolph et al. (1980)

**Yields and yield changes from baseline for dryland corn in 2030 and 2095 under HadCM2 GCM climate scenarios**

- Izaurralde et al. (2003)

**Modeled yields of wheat and maize as affected by CO$_2$ concentration and climate change in four regions: Northern Plains (NP), Southern Plains (SP), Lakes (LK) and Corn Belt (CB)**

**Wheat yield (Mg ha$^{-1}$)**

- Izaurralde et al. (2003)

**Modeled water use efficiency (WUE) in wheat and maize as affected by CO$_2$ concentration and climate change in four US regions: Northern Plains (NP), Southern Plains (SP), Lakes (LK) and Corn Belt (CB)**

**Wheat WUE (kg ha$^{-1}$ mm$^{-1}$)**

- Izaurralde et al. (2003)

**Climate change may bring significant changes (and conflicts) between water supply and demand**

- Izaurralde et al. (2003)

- Proxy measure of water supply and demand
  - WY = IRR
  - WY from HUMUS
  - IRR from EPC

- Supply / demand relationship

$$R_{WY} = \frac{\Delta(WY - IRR)_{\text{current}}}{WY - IRR}_{\text{baseline}}$$

**Climate Change on Water case studies in India and China Using the SWAT model**
Impact studied

- Impact on annual water availability
- Impact on seasonal water availability
- Impact on inter annual water availability
- Regional Variability of Water availability

Percent change in mean annual water balance for Control and GHG climate scenarios

Trend in Precipitation, Runoff and Evapotranspiration for Control and GHG Climate Scenarios

Drought Analysis

- Graduated colour depicts spatial variability of concurrent severity of drought, number of sub-basins where severe concurrent conditions prevailed in a year,
- Size of the green dot reveals the number of drought weeks experienced in each sub-basin over the 20 years.

Spatial and temporal distribution of drought conditions

- Sabarmati and Mahi, sever drought conditions in comparison to control scenario
- Mahanadi and Brahmani, the drought conditions seem to improve in the GHG scenario
**Flood Analysis**

- Annual maximum daily peak discharges for two sub-basins of Mahanadi and Brahmani river basins for Control and GHG scenarios.

**Mahanadi River Basin**

**Brahmani River Basin**

**Potential Future Climate Change**

- **Two GCMs**
  - HadCM3 by U.K. Meteorological Office Hadley Centre for climate prediction and research
  - CGCM2 model developed by the Canadian Centre for Climate Modelling and Analysis

- **Two Emission scenarios**
  - The A2 scenario projects high population growth and slow economic and technological development
  - While the B2 scenario projects slower population growth, rapid economic development, and more emphasis on environmental protection.

- **Eight future climate conditions**
  - 2050 (H2050A2, H2050B2, C2050A2, C2050B2)

**Key Findings**

- Under the GHG scenario the conditions may deteriorate in terms of severity of droughts in some parts of the country and enhanced intensity of floods in other parts.
- There is a general overall reduction in the quantity of the available runoff under the GHG scenario.
- Luni with the west flowing rivers Kutch & Saurashtra which occupies about one fourths of the area of Gujarat and 60 percent of the area of Rajasthan shall have acute physical water scarce conditions.
- River basins belonging to Cauvery, Ganga, and Narmada shall experience seasonal or regular water stressed conditions.
- River basins belonging to Godavari, Brahmani and Mahanadi shall have rare water shortages and if exist they are only confined to few locations.

**Downstream of Luohe River Basin**

- During 1961-1990, the average flow rate at the Baimasi hydrological station was about 55 m³ s⁻¹
- While in the 1990s, the average flow rate decreased to approximately 30 m³ s⁻¹.

**Model Calibration and Validation**

**Potential Future Climate Change**

- Annual and monthly average temperature changes (°C) under various scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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</table>

- Annual and monthly cumulative precipitation changes (mm) under various scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<td>H2050A2</td>
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<tr>
<td>H2020B2</td>
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</table>
**Annual Streamflow Change**

- In 2020, the predicted streamflow change is within ±3%.
- In 2050, possible annual streamflow changes are expected to range between +6% and +11%.

![Annual Streamflow Change Graph](image)

**Seasonal Streamflow Change**

- In 2020, the predicted streamflow changes ranged from -4% to +2% in winter, from +1% to +20% in spring, from -2% to +12% in summer, and from -9% to +6% in autumn.

![Seasonal Streamflow Change Graph](image)

**Monthly Streamflow Change**

- In 2020, the possible streamflow change in January, February, March, July, August, September, and October is within ±10%. In the other months, the maximum possible streamflow change was predicted to be within ±20%, except for May, which showed a maximum possible streamflow change reaching +35%.

![Monthly Streamflow Change Graph](image)

**Climate Change and Agriculture: Adaptation and Mitigation**

- In 2050, the possible streamflow change amplitude in January, February, and March was within ±10%. In other months, this change was within ±20%, again except for May, which had predicted streamflow changes reaching +60%.
Adaptation, Mitigation, and Vulnerability: Definitions

- **Adaptation**: an action designed to lessen adverse impacts of climate change on human and natural systems.
- **Mitigation**: an action designed to counteract emissions and concentrations of greenhouse gases and aerosols in the atmosphere.
- **Vulnerability**: extent to which climate change may harm a system.

Impacts of land use change and management on soil and environmental quality

- Land use and land use change have affected:
  - Soil and environmental quality
  - Terrestrial carbon stocks
- Preservation of land and water quality is essential to address climate change.

Carbon Sequestration: Carbon removal from the atmosphere

- **Natural sinks**
  - Forests
  - Oceans
- **Enhanced sinks**
  - Forests
  - Soils
  - Oceans
- **Artificial sinks**
  - Geologic sequestration

Forest Carbon Sequestration:
An accepted mitigation technology with finite potential (40 Pg C)

- **Reforestation**
- **Afforestation**

Land Use change and soil management effects on SOM levels

- **Cultivation**
  - Carbon oxidation and nutrient mineralization
- **Erosion**
  - Wind and water
  - Improved practices
  - Agricultural systems
  - Land use conversions

Historical development of croplands

Global distribution of soil organic C (ISRIC, 2002)
Soil Carbon Sequestration: A near term mitigation technology with significant but finite potential (40 Pg C)

The southeastern USA has seen significant adoption of no-tillage in cotton production systems

- As of 2004, there were 2.9 Mha (~24% of total cropland) under cotton production in the southeastern USA
- Of this land, 34% was under conservation tillage (mostly no-tillage), 17% under reduced tillage, and 48% under conventional tillage

No-tillage cotton production systems increase soil carbon in the southeastern USA

470 kg C ha⁻¹ yr⁻¹


Understanding management effects on soil organic C dynamics

- Breton C 13 Classic soils
  - Forest to agriculture in ~1900
  - Experiment initiated in 1930
  - Current treatments (1998)
  - Crop rotations
    - Fallow
    - Conventional
    - Intermittent
  - Fertilizer treatments
    - Corn
    - Phosphate
    - Feed
    - None

Full Carbon Accounting in Agroecosystems

1. Soil C Oxidation
2. Fuel
3. Nitrogen Fertilizer
4. Lime (CaCO₃) and Ca in Irrigation Water
5. Non-CO₂ Greenhouse Gases
   - N₂O
   - CH₄

KBS Long-Term Ecological Research (LTER) Site


<table>
<thead>
<tr>
<th>Ecosystem Type</th>
<th>Management Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Crops (Corn - Soybean - Wheat)</td>
<td>High</td>
</tr>
<tr>
<td>Conventional tillage</td>
<td></td>
</tr>
<tr>
<td>No-till</td>
<td></td>
</tr>
<tr>
<td>Low input with legume cover</td>
<td></td>
</tr>
<tr>
<td>Organic with legume cover</td>
<td></td>
</tr>
</tbody>
</table>

Successional Communities:
- Early successional old field
- Mid successional old field
- Late successional forest

Low
**Biomass Energy Crops**

- Plant biomass can be used to produce liquid fuels, electricity, and heat
  - Agricultural crops (grain and residues)
  - Forest residues
  - Municipal solid wastes
- New traits for biomass energy crops
  - Attributes
    - Native, perennial, fast growing, pest resistant, non-agrochemical
  - Examples
    - Switchgrass
  - Paper
- Research needs
  - Examine their role on land use and competition with food and fiber crops
  - Evaluate impacts on managed and unmanaged ecosystems

**Can we adapt to climate change?**

- In general, societies have exhibited a good degree of adaptation to weather and climate conditions
  - Agriculture: crop varieties, agronomic practices, water management
  - Urban centers: disaster management, insurance
- However, climate change presents risks of unknown consequences
  - Permafrost melt (and release of greenhouse gases)
  - Accelerated glacier retreat

**Adaptation in agriculture**

- 2nd IPCC report
  - "...global agricultural production can be maintained relative to baseline production in the face of climate changes..."
- 3rd IPCC report
  - "...downward trend in real commodity prices in the 20th century is likely to continue into the 21st century, although confidence in these predictions decreases further into the future..."

**The geographic center of crop production in the US has changed over time: Adaptation to climate change?**

- Temporal changes in the wheat production zone from 1920 to 1995 (Rosenberg et al. 1982, Easterling et al., 2004)
- Geographic centers of production of corn, soybean, and wheat (Huff et al. 2003)

**The MINK study: a pioneer study of climate change impacts on agricultural production and the need for adaptation**

- Region selected for
  - Physiographic homogeneity
  - Vulnerability of natural and socio-economic resources to climate change
- The study used
  - Historical climate records as analogs of climate change (The Dust Bowl of the 1930s)
  - Biophysical modeling of "representative farms"
    - Climate parameters
    - Soil properties
    - Management practices


**Adaptation strategies in the MINK region**


- Planting and harvesting strategies
  - Planting dates
  - Planting depth
  - Reduce plant density
- Land management
  - Reduce tillage
  - Conserve moisture
    - Fallow
    - Stubble mulch
    - Ridge
- Variety and crop selection
  - Switch to shorter or longer season cultivars
  - Select stress tolerant crops
  - Convert marginal land to pasture or range
- Fertility and pest management
  - Biological N fixation
  - Reduce N application
  - Chemical weed control
The time to start adapting to climate change is now

- UN Climate Change Conference held in Nairobi, Kenya in November 2006
  - Clear message on the need for adaptation
  - Even if emissions were to be stopped now, greenhouse gases already in the atmosphere will continue to induce global warming
- International, national, and local organization already taking action

Summary of expected effects of global warming on agricultural crops

- An increase in temperature over the next decades will likely reduce yields of important crops such as maize, wheat, cotton, sorghum, and peanut
- The increase of atmospheric CO₂ in the next decades could favor the yields of C3 species over C4 species due the so-called CO₂-fertilization effect (i.e. increased photosynthesis and water use efficiency)
- All crops will be subject to increased recurrence of extreme climatic conditions (e.g. droughts, extreme temperatures)

Summary

- There is scientific evidence that humans are in good part responsible for ongoing changes in the climate system
- A global effort will be required to stabilize greenhouse gases to levels that are non-damaging for humanity and ecosystems
  - Mitigation (improved efficiency in energy use, new energy technology, carbon capture and sequestration)
  - Adaptation (prepare social and natural systems for climate change)
- Cotton production maybe affected in the future by a variety of environmental factors
  - Increases in temperature, especially during reproductive stages, will lead to decreases in boil yields
  - If present, the CO₂ fertilization effect may ameliorate the negative effects of temperature and even result in yield increases
  - Cotton plants will be subject to more extreme conditions (e.g. droughts, extreme temperatures) or presence of pollutants (e.g. tropospheric ozone)
  - Increasing organic matter in soils might be one of the best ways to ensure the long-term sustainability of cotton production

Acknowledgements

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  - Integrated Assessment Research Program
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  - The Modeling of Regional Climate over China