A New Era in Global Change Science:
Linking Knowledge and Action for Sustainability

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School of Earth Sciences
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The most critical challenge of the 21st Century:

Meeting the needs of people today and in the future

Sustaining the life support systems of the planet

NRC. 1999. Our Common Journey
Social needs are not being met

1 – 2 billion persons are…

• illiterate adults
• without adequate shelter
• without access to safe water or sanitation
• without access to electricity
• undernourished

7,000,000,000
Life support systems are degraded

- Air Pollution
- Climate change
- Acidification of the oceans
- ~50% land surface has been converted
- Biodiversity loss 100+ times faster
- 60% of ecosystem services in decline
- Water and soil resources limitations
- Nitrogen over-enrichment
- Mineral resource limitations
Meeting the needs of people today

Sustaining atmosphere, water, climate and ecosystems
Meeting the needs of people today

Sustaining atmosphere, water, climate and ecosystems
A *Transition* to Sustainability

What will it take?
What will it take for a transition to sustainability?

- new knowledge, tools and approaches
- linking knowledge to action
- educating leaders and the public
- hope, inspiration, and motivation
- the will to change
- Institutions and governance to help
- leadership by corporations, citizens, governments, non-profits, universities
  (and a stable human population....)
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*Decades of research have dramatically improved understanding*
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Advancing the Science of Climate Change

What do we know?
What more is needed?

-Full text online,
-PDF Summary,
-4-page “report in brief”
-short video summary

americasclimatechoices.org
“Climate change is occurring, is caused largely by human activities, and poses significant risks for (and in some cases is already affecting) a broad range of human and natural systems.”

This conclusion is based on a broad array of evidence and is consistent with conclusions by the Intergovernmental Panel on Climate Change (IPCC), the U.S. Global Change Research Program (USGCRP), and other groups.

NRC 2010
The planet’s average surface temperature rose by 1.4°F between the first decade of the 20th century (1900-1909) and the first decade of the 21st century (2000-2009), with the sharpest warming (~1.0°F) over the past three decades.
And other indications of climate change

- Ocean temperatures warming
- Ice Sheets and Glaciers are melting
- Sea level increasing
- More intense and frequent heat waves
- Growing season lengthening
- Earlier spring migration
- Forest fires increasing
- Snow pack declining
Role of Human Activities

- Greenhouse gas concentrations in the atmosphere are increasing as a result of human activities.
- Observed increases in carbon dioxide and other greenhouse gases can be unambiguously linked with human activities, especially burning fossil fuels for energy.

... and isotopic measurements provide a smoking gun.

Based on data from Boden et al. (2009); Keeling et al. (2009); Neftel et al., (1994)
Other causes?

Other possible causes of warming have been rigorously tested and ruled out; these include:

- Natural climate variations, which historical records and climate models suggest cannot explain the observed rate and pattern of recent warming
- **Solar output**, which has not increased in the last 30 years (but may have risen slightly in the early 20th century)
- Cosmic rays or changes in volcanic activity, which likewise do not show a trend during recent decades

Source: Lean and Woods, 2010

NRC 2010
Role of Human Activities

Conclusion: Other factors also influence climate, but anthropogenic greenhouse gases dominate the warming.

Radiative forcing of climate between 1750 and 2005

- Warming due to carbon dioxide
- Warming due to other greenhouse gases
- Changes in land use (mixed/small)
- Cooling due to aerosols (small particles that reflect sunlight back to space)
- Warming due to solar changes (small)

Total human-induced warming

NRC 2010
But what about the future??

The future is uncertain....

Uncertainties arise primarily because:

(1) we don’t know how human societies will produce and use energy in the decades ahead, so we use various scenarios
Projections of Future Climate Change Based on 3 Different Scenarios

Model projections of future climate change, based on three different scenarios of future emissions.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Scenario</th>
<th>Temperature Range (°F)</th>
<th>Global Average Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1: 2080-2099</td>
<td>A1B: 2080-2099</td>
<td>3.6-9.7°F</td>
</tr>
</tbody>
</table>

These changes are in addition to the already-observed 1.4°F increase.

Source: Meehl et al, 2007
Uncertainties arise primarily because:
(1) we don’t know how human societies will produce and use energy in the decades ahead, so we use various scenarios
(2) we don’t know exactly how much warming will result from a given amount of GHG emissions (our models and understanding are incomplete)
Air pollution masks part of the greenhouse gas warming...so what happens when we clean it up?
Feedbacks and Tipping Points

Boreal forests underlain by permafrost
Projections of Future Climate Change

There may be unexpected *feedbacks* or *tipping points* that lead to rapid warming, irreversible changes, or severe impacts.
Uncertainties arise primarily because:

(1) we don’t know how human societies will produce and use energy in the decades ahead, so we use various scenarios

(2) we don’t know exactly how much warming will result from a given amount of GHG emissions (models and understanding are incomplete)

(3) we don’t know all of the impact relationships nor include them in models
Linked Models for Projections of Future Impacts

Emissions → Climate Response → Agricultural Systems → Economics and Trade → Hunger Impact
So, the future is uncertain (projections of the future are ALWAYS uncertain)

... this does not mean that nothing is known about how climate change will unfold

In fact, we know a lot about the potential impacts and risks associated with climate change, and about steps that can be taken to respond...
Impacts of Climate Change

Example: Sea Level Rise

Sea levels are rising, and will continue to do so.

How much and how fast depends mainly on how fast ice sheets and glaciers melt.

Source: Vermeer and Rahmstorf (2009)
Impacts of Climate Change

Example: Sea Level Rise

Sea level rise poses significant challenges to societies and to ecosystems.

Moral: the future is uncertain, but carries substantial risks (unless actions are taken to reduce those risks)

Source: Overpeck and Weiss (2009)
Impacts of Climate Change

Example: Freshwater Resources

- The global water cycle is “speeding up”, which tends to make wet places wetter and dry places drier.
- A higher fraction of rainfall is also coming in the form of heavy precipitation, which leads to flooding.
- Changes in snow and ice cover also affect water availability and quality.

Photo credit: USGCRP, 2009

NRC 2010
Increases in Amount of Precipitation Falling in Very Heavy Precipitation Events (1958-2007)

USGCRP Impacts report 2009
Impacts of Climate Change

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Photo credit: USGCRP, 2009

NRC 2010
Predicted Decreases in Snowpack

Increasing Warming

- Historical Average (1961–1990)
- 100% remaining

- Lower Warming Range
  - Drier Climate
  - 40% remaining

- Medium Warming Range
  - Drier Climate
  - 20% remaining

April 1 snow water equivalent (inches)

CA Climate Change Center 2006
More Impacts That Matter For Human Well-being

• Heat Waves
  – Increased mortality rates, especially in cities

• Air Quality
  – More severe pollution events (due to higher temperatures)

• Forests
  – Increased risk of wildfire, vulnerability to insects, decreased growth & regeneration

• Crop Production
  -- With more than a few degrees warming, decreased yields of most current crops (not counting possible negative effects of flooding, heavy rain, insects, heat spells, lack of irrigation water)

CA Climate Change Center Summary Report (2006)
Life support systems are degraded

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- Mineral resource limitations
Anthropogenic Change in the Nitrogen Cycle

[Diagram showing the nitrogen cycle with anthropogenic and natural cycles highlighted.]
Terrestrial N Budget

Background
- Biological N Fixation 58
- Lightning 4

Anthropogenic
- Industrial Fertilizer 105
- Other Industrial 20
- Fossil Fuel 25
- Legume Crop 50
Agricultural fertilization is the source of increasing nitrous oxide concentrations

Source: IPCC Third Assessment Report, 2001
Global Atmospheric Deposition of Anthropogenic Nitrogen

mg N/ m²/ y

Dentener, pers com
Anthropogenic Nitrogen Drives Hypoxia in Coastal Waters

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Loss of Ecosystem Services

Seafood
Food Crops & Livestock
Forest Products
Energy Crops

Carbon storage
Provision of Water
Fire Prevention
Flood Control
Sedimentation Control
Pest Control
Pollination

Spiritual Values
Educational Values
Inspiration
Aesthetic Values
Social Relations
Sense of Place
Recreation
Tourism

Options: e.g., Biodiversity
## Status of Provisioning Services

<table>
<thead>
<tr>
<th>Service</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td></td>
</tr>
<tr>
<td>crops</td>
<td>↑</td>
</tr>
<tr>
<td>livestock</td>
<td>↑</td>
</tr>
<tr>
<td>capture fisheries</td>
<td>↓</td>
</tr>
<tr>
<td>aquaculture</td>
<td>↑</td>
</tr>
<tr>
<td>wild foods</td>
<td>↓</td>
</tr>
<tr>
<td>Fiber</td>
<td></td>
</tr>
<tr>
<td>timber</td>
<td>+/-</td>
</tr>
<tr>
<td>cotton, silk</td>
<td>+/-</td>
</tr>
<tr>
<td>wood fuel</td>
<td>↓</td>
</tr>
<tr>
<td>Genetic resources</td>
<td>↓</td>
</tr>
<tr>
<td>Biochemicals, medicines</td>
<td>↓</td>
</tr>
<tr>
<td>Fresh water</td>
<td>↓</td>
</tr>
<tr>
<td>Regulating Services</td>
<td>Status</td>
</tr>
<tr>
<td>---------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Air quality regulation</td>
<td>↓</td>
</tr>
<tr>
<td>Climate regulation – global</td>
<td>↑</td>
</tr>
<tr>
<td>Climate regulation – regional and local</td>
<td>↓</td>
</tr>
<tr>
<td>Water regulation</td>
<td>+/-</td>
</tr>
<tr>
<td>Erosion regulation</td>
<td>↓</td>
</tr>
<tr>
<td>Water purification and waste treatment</td>
<td>↓</td>
</tr>
<tr>
<td>Disease regulation</td>
<td>+/-</td>
</tr>
<tr>
<td>Pest regulation</td>
<td>↓</td>
</tr>
<tr>
<td>Pollination</td>
<td>↓</td>
</tr>
<tr>
<td>Natural hazard regulation</td>
<td>↓</td>
</tr>
<tr>
<td><strong>Cultural Services</strong></td>
<td></td>
</tr>
<tr>
<td>Spiritual and religious values</td>
<td>↓</td>
</tr>
<tr>
<td>Aesthetic values</td>
<td>↓</td>
</tr>
<tr>
<td>Recreation and ecotourism</td>
<td>+/-</td>
</tr>
</tbody>
</table>
60% of Ecosystem Services are in decline…

“Running down the account”

Millennium Ecosystem Assessment 2005
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What will it take for a transition to sustainability?

- new knowledge, tools and approaches

*Decades of research have dramatically improved our understanding of how and why the planet is changing*
Understanding ---> Solutions?
“call to arms” for R&D focused on both understanding and problem solving
Understanding ---> Solutions?

*reorientation of research* so that science can better address the needs of decision makers

*Use-inspired research*,
focused on problem solving in coupled human-environment systems
Example: Science to Support Responses to Climate Change

Two major categories of responses to climate change:

- Limiting the magnitude of climate change
- Adapting to the impacts of climate change

Scientific research plays a key role in informing and expanding the options available to respond to climate change.

NRC 2010
Limiting Climate Change

• reduce consumer demand
• increase efficiency of energy use
• develop and use low and no-carbon energy sources
• capture and sequester carbon
• reduce deforestation
• reduce other GHG emission (agriculture)
Limiting Climate Change

- reduce consumer demand
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Energy Alternatives

Solar
Wind
Water
Ocean sources
Nuclear
Geothermal
Biofuels

Fuel switching
Carbon capture and storage
Energy Alternatives

Technology?

Land competition with food production, conservation?

Water resources?

Other GHG and pollutants?

Health and nutrition?

Trade and security issues?

Implementation barriers?

Solar
Wind
Water
Ocean sources
Nuclear
Geothermal
Biofuels
Responding to Climate Change

Limiting the Magnitude of Climate Change

Scientific research can help…

- Developing and improving technologies, management strategies, and institutions to reduce net greenhouse gas emissions from energy production and use and from agriculture and land use.
- Improving understanding of behavioral and sociological factors related to the adoption of new technologies, policies, & practices
- Developing tools and approaches for choosing among options, preventing unintended consequences, and identifying co-benefits

NRC 2010 Advancing the Science of Climate Change
Adapting to the Impacts of Climate Change

Freshwater Resources

Coastal Vulnerabilities

Agriculture and Food Production
Responding to Climate Change

Adapting to the impacts of climate change

Scientific research can help:

- Characterizing impacts and vulnerability
- Developing and improving technologies and strategies to reduce vulnerability and/or increase adaptive capacity
- Analyzing the effectiveness of adaptation measures
- Developing tools and approaches for choosing among options, preventing unintended consequences, and identifying co-benefits

NRC 2010 Advancing the Science of Climate Change
What will it take for a transition to sustainability?

- new knowledge, tools and approaches for understanding and problem solving

*We’re making progress…but recent “call to arms” is important…*
What will it take for a transition to sustainability?

- new knowledge, tools and approaches
- linking knowledge to action
What will it take for a transition to sustainability?

- new knowledge, tools and approaches
- linking knowledge to action

*Even the relevant knowledge that does exist is too seldom made available in ways that can support decisions, action...*
The “pipeline” model of knowledge and technology transfer rarely works....
How can we most effectively link knowledge with action for sustainability??
How can we most effectively link knowledge with action for sustainability?

- Public Opinion and Perception
- Decision Making under Uncertainty
- Decision Networks and Decision Support

“Knowledge Systems” -- networks of actors and organizations that perform a number of knowledge-related functions that link knowledge and know-how with action and decision making.
How can we most effectively link knowledge with action?

What works and why, from analysis of case studies.

NRC Roundtable on Science and Technology for Sustainability, Clark et al NOAA study
A vignette: Sustainability Challenges in the Yaqui Valley

Creating new knowledge, and linking knowledge to action

Matson, Naylor, Ortiz-Monasterio
…and a multi-disciplinary team

Matson 2012 Seeds of Sustainability
“the birthplace of the Green Revolution”

Figure 3. Comparison of world wheat yields to the Yaqui Valley.
Source: FAO Production Yearbook, CIMMYT.
Many different sustainability challenges:

- Water resources overuse and competition
- Over-fertilization in agricultural systems
- Shrimp aquaculture explosion
- Vulnerability to climate change
- Drinking water quality and human health
- Air pollution and human health
- Loss of ecosystems and services
- Poor urban infrastructure
- Emigration and demographic change
- Social inequities

…
Many different sustainability challenges:

Water resources overuse and competition
Over-fertilization in agricultural systems
Shrimp aquaculture and coastal zone change
Vulnerability to climate change
Drinking water quality and human health
Air pollution and human health
Loss of ecosystems and services

...
Fertilizer was heavily subsidized as part of the GR technologies
Increasing rates of fertilizer application

Nitrogen applied to wheat in Yaqui Valley, kg/ha

Year

Nitrogen kg/ha


Percentages represent proportion of wheat area fertilized.

Source: SARH, CIANO, CIMMYT database.
Fertilizer over-use leads to nutrient losses and environmental impacts through several pathways.
Nutrient losses to freshwater bodies and coastal estuaries and the Gulf of California
Fertilization and Irrigation Events Drive Massive Phytoplankton Blooms (50-600 km²)

Beman, Arrigo and Matson 2005
Regional-Scale Impacts
Losses of fertilizer affect down-wind and down-stream systems

Downstream

NO$_3^-$ Input to Marine

NO$_3^-$ and NH$_4^+$ (In Surface and Ground water)

Marine Ecosystems

NO

N$_2$O (Greenhouse gas)

Cropping Systems

Downwind

NO$_x$ (air pollutant)

Urban

N Deposition

Ecosystems of the Sierra Madre
Agriculture in the Yaqui Valley

Fertilizer Use and Biogeochemical Consequences

Economic drivers and consequences

Agronomic constraints, alternatives, and barriers to change
Are there win-win alternatives?

Field experiments

Agro-ecosystem simulation models

Economic analyses
Win-Win Options that Save Farmers Money and Reduce Environmental Consequences

Apply Less Fertilizer, Timed to Crop Demand

Maintain Yields and Increase Grain Quality

Reduce Nitrogen Loss Pathways

Save 12-18% of After-tax Profits

* Field Experiments, On-Farm Analyses, and Simulation Modeling at Regional scale

win-win!
Knowledge → Action?
<table>
<thead>
<tr>
<th>Year</th>
<th>Kg N/ha</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>1966</td>
<td></td>
<td>84%</td>
</tr>
<tr>
<td>1981</td>
<td></td>
<td>64%</td>
</tr>
<tr>
<td>1997</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

Percentage represents the proportion of the area that is fertilized.
Percentage represents the proportion of the area that is fertilized
But Nitrogen Fertilizer Use Continued to Increase…

Percentage represents the proportion of the area that is fertilized

Matson 2012 Seeds of Sustainability
Understanding and Mapping the Knowledge System

“networks of actors and organizations that perform a number of knowledge-related functions that link knowledge and know-how with action and decision making”
Knowledge --> action???
What drives fertilizer management decisions?
Credit Union Advice
And...Risk aversion due to uncertainty related to variability in soils and climate...
Solution: Use site specific management to reduce uncertainty leading to reduction in fertilizer use....and work with farmers and credit union advisors to test and incorporate new approaches.

Real-time measurements of plant N relative to fertilized strips

Ortiz Monasterio et al.
SEEDS
of
SUSTAINABILITY

LESSONS FROM THE BIRTHPLACE
of the
GREEN REVOLUTION IN AGRICULTURE

Edited by Pamela A. Matson
Lessons from Case Comparisons

Three critical barriers:

1) Mutual miscomprehension (and distrust) between decision makers and scientists
2) Fragmentation of the knowledge system
3) Inflexibility in a world of surprise and uncertainty
Lessons from Case Comparisons

Three critical barriers:

1) Mutual miscomprehension (and distrust) between decision makers and scientists
2) Fragmentation of the knowledge system
3) Inflexibility in a world of surprise and uncertainty
Reject the “pipeline” model of knowledge and technology transfer

- Promote *multi-directional, on-going information flow and dialogue*

- Promote *collaborative production* of trusted knowledge, involve stakeholders in its creation

Clark, Matson, Lebel, Gallopin, et al
Foster “boundary-spanning” capabilities

Successful systems almost always include trusted individuals or organizations devoted to the task of “boundary spanning” across cultures

Clark, Matson, Lebel, Gallopin, et al
Yaqui Case:
Dr. Ivan Ortiz Monasterio = Boundary Individual
In the 2000’s, Credit Unions were also boundary organizations…. 

Agriculture Knowledge System, Yaqui Valley 050610
Boundary spanning is often facilitated by boundary “objects”

Yield (Y) = \{ f \text{ Temperature, Soil, Management} \}

Source: Lobell et al. 2002
“Over-fertilization equals money down the drain…”.

Beman, Arrigo and Matson 2005
Lessons from Case Comparisons

Three critical barriers:

1) Mutual miscomprehension between scientists and decision makers

2) Fragmentation of the knowledge system

3) Inflexibility in a world of surprise and uncertainty

Clark, Matson, Lebel, Gallopín, et al
Different organizations often are charged with different parts of the knowledge-action chain…

- But sustainability is often a public good, with weak incentives to complete the chain from basic research to large-scale adoption

- Need to treat system like “supply chain” and construct incentives to complete it

Clark, Matson, Lebel, Gallopin, et al
What will it take for a transition to sustainability?

- new knowledge, tools and approaches
- linking knowledge to action

*Purposefully design or engage in systems that connect knowledge and know-how with action*
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( and a stable human population... )
IMAGINE!