

# Earth System Research for Global Sustainability

WCRP  
Open Science Conference  
Denver, Colorado, 29th Oct  
2011



Prof. Johan Rockström  
Stockholm Resilience Centre  
Stockholm Environment Institute

**Stockholm Resilience Centre**  
Research for Governance of Social-Ecological Systems



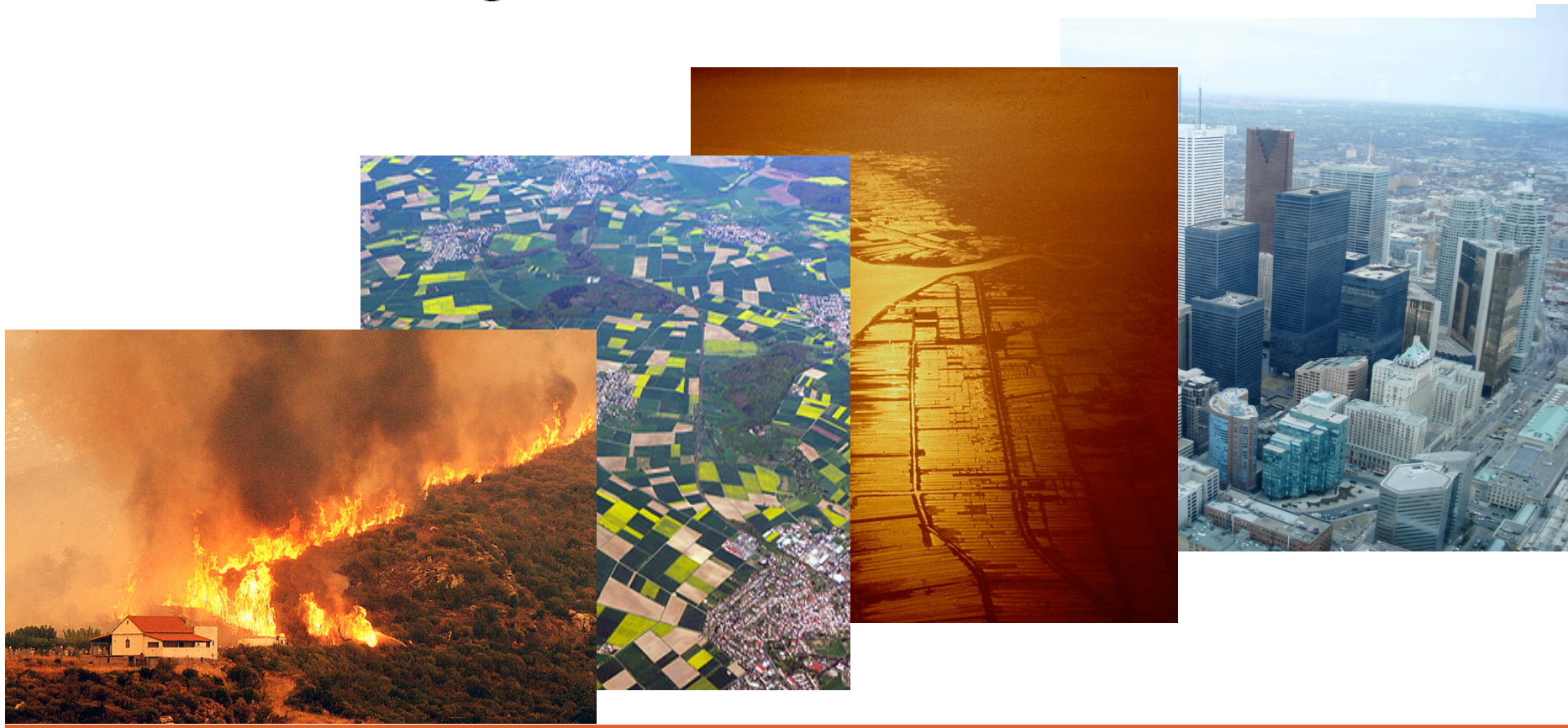
A centre with:



Article

Will Steffen, Paul J. Crutzen and John R. McNeill

# The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?



**Stockholm Resilience Centre**  
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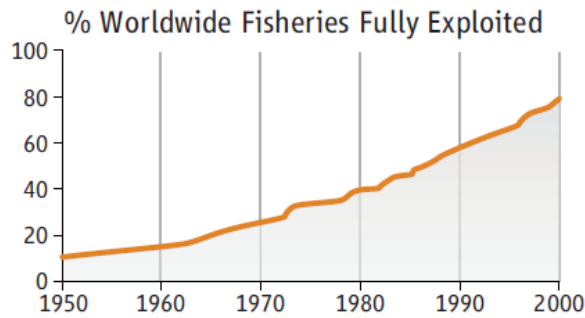


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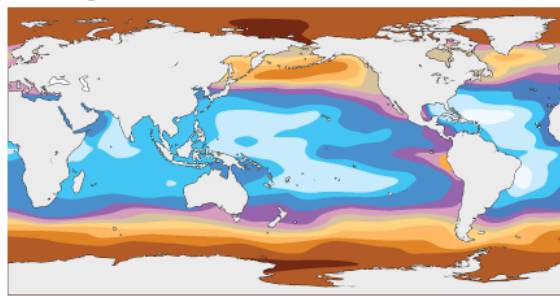
# A Global Perspective on the Anthropocene

www.sciencemag.org SCIENCE VOL 334 7 OCTOBER 2011



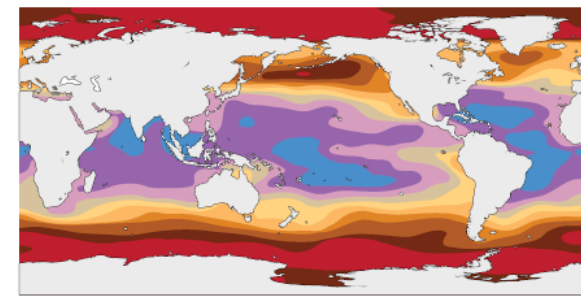
SOURCE: WILL STEFFEN ET AL., *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A* 369 (2011)

Getting More Acidic



CO<sub>2</sub> 280 PPM

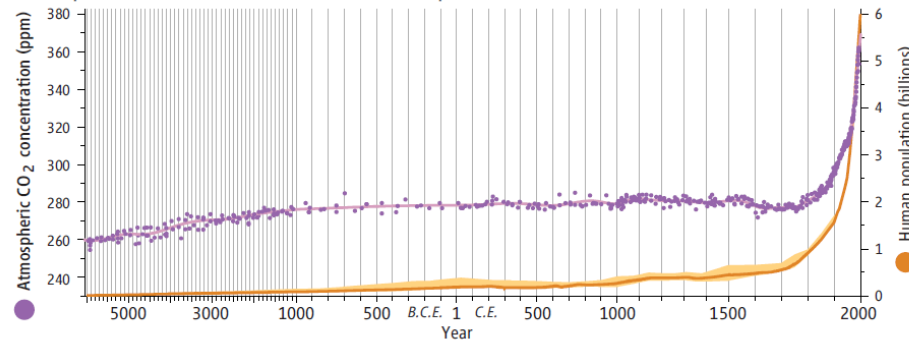
Aragonite saturation state 1 2 3 4 5



CO<sub>2</sub> 450 PPM

SOURCE: O. HOEGH-GULDBERG ET AL., *SCIENCE* 318, 5857 (14 DECEMBER 2007)

Atmospheric CO<sub>2</sub> Concentration vs. Human Population



SOURCE: JED O. KAPLAN ET AL., *THE HOLOCENE* 21, 5 (AUGUST 2011)



Humanity has reached a planetary saturation point

A resilient biosphere the basis for human development

Climate change one interacting component of global sustainability

A great transformation to global sustainability necessary, possible, and desirable

“We have our foot on the accelerator driving towards the abyss...”

Ban Ki-moon Secretary General of the UN

“We are destabilizing our climate *and* stretching planetary boundaries to a perilous degree”.



# Rio+20 and a transition to Global Sustainability



## UN Secretary General Ban Ki-Moon High Level Panel on Global Sustainability

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*”When reality is changing faster than theory suggests it should, a certain amount of nervousness is a reasonable response”  
The Economist*

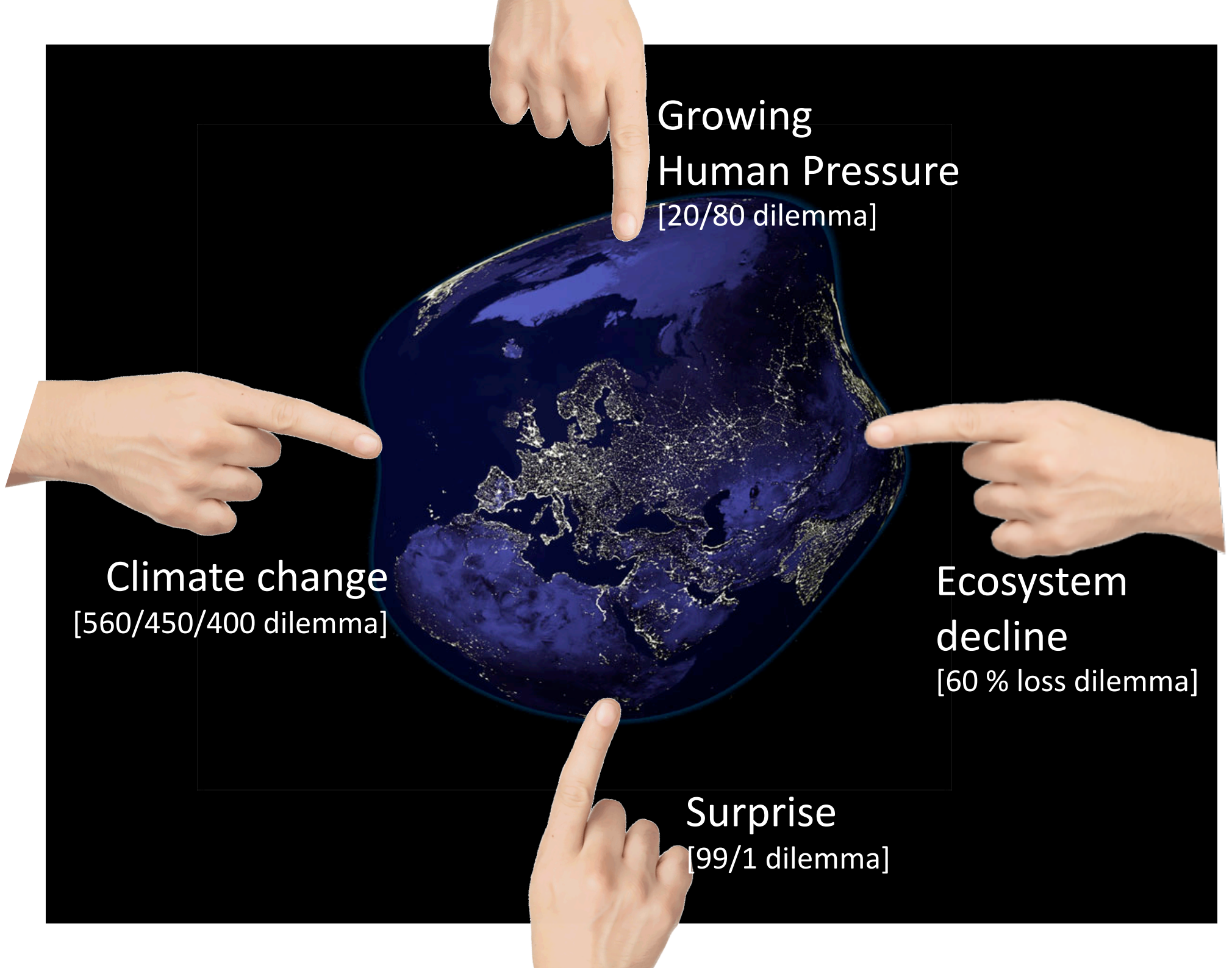


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Growing  
Human Pressure  
[20/80 dilemma]

Climate change  
[560/450/400 dilemma]

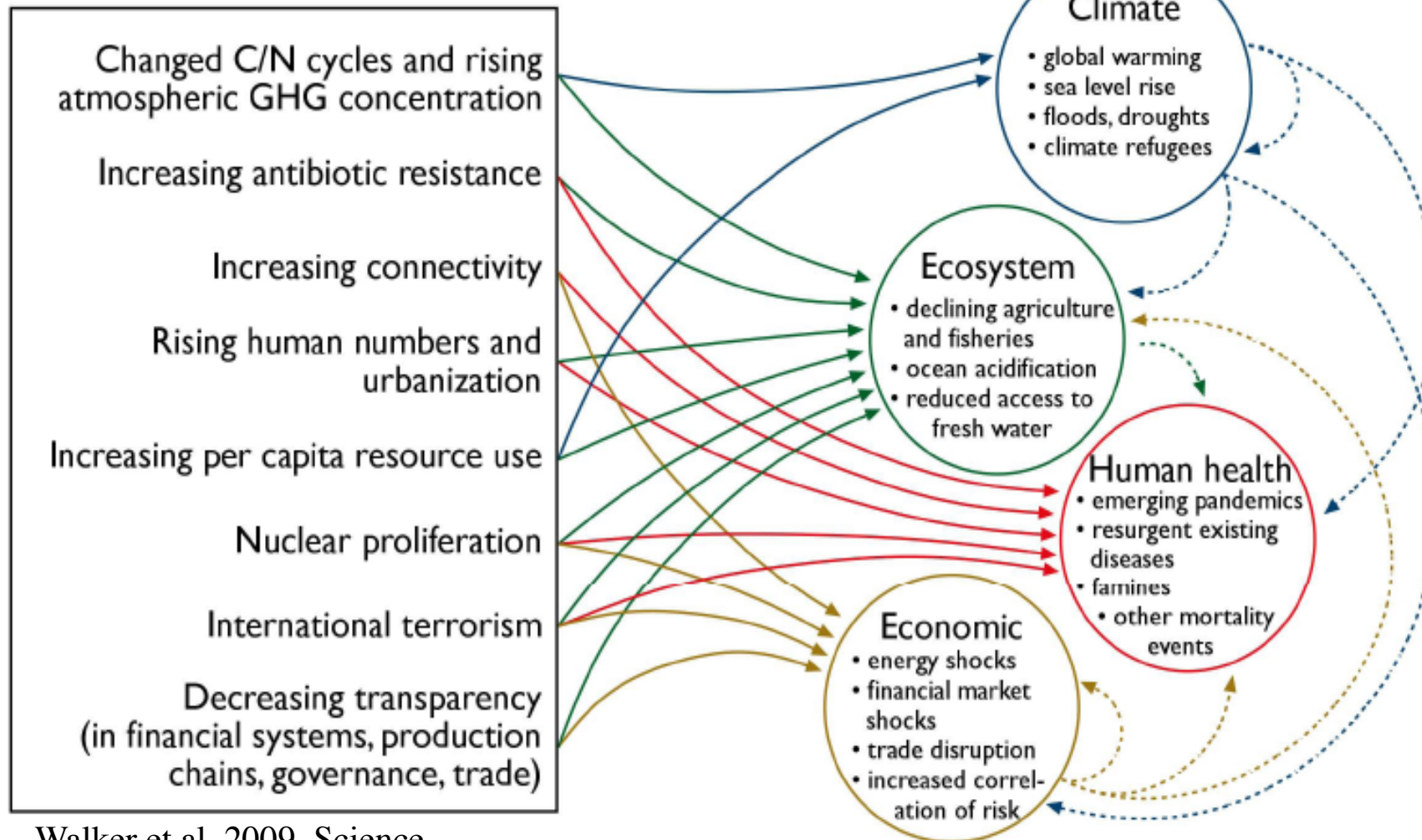
Ecosystem  
decline  
[60 % loss dilemma]

Surprise  
[99/1 dilemma]



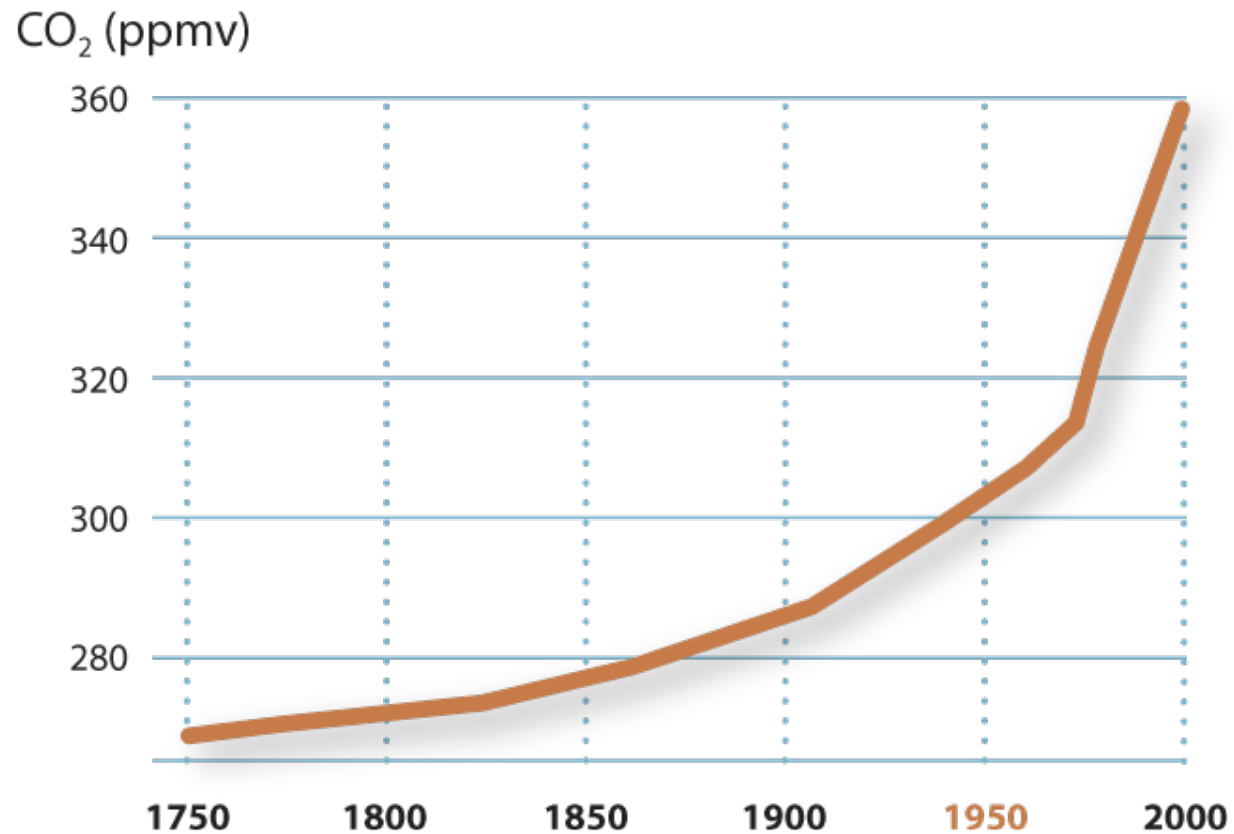
## Global drivers (exogenous and endogenous)

## Unwanted outcomes



Walker et al. 2009. Science

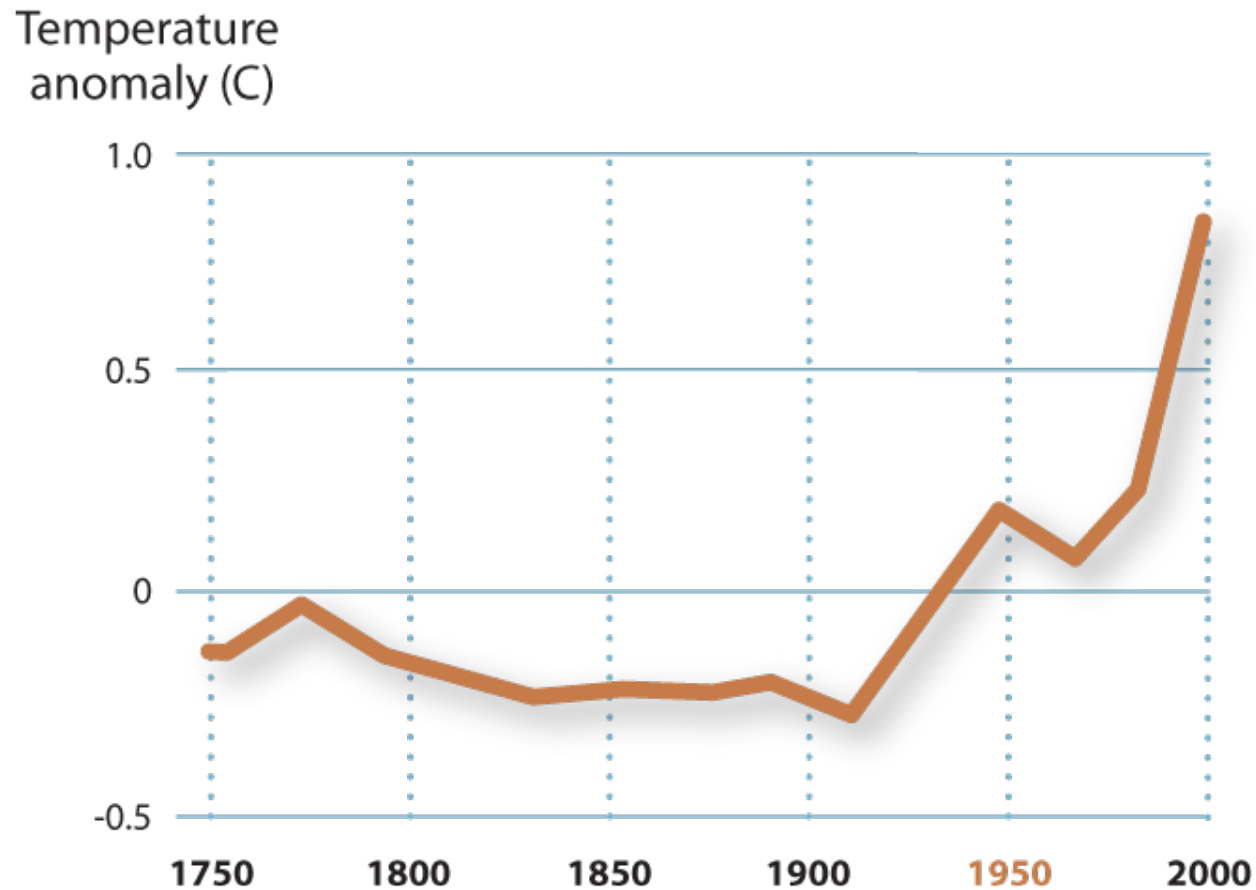
# Atmospheric CO<sub>2</sub> concentration



Etheridge et al. Geophys Res 101: 4115-4128

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

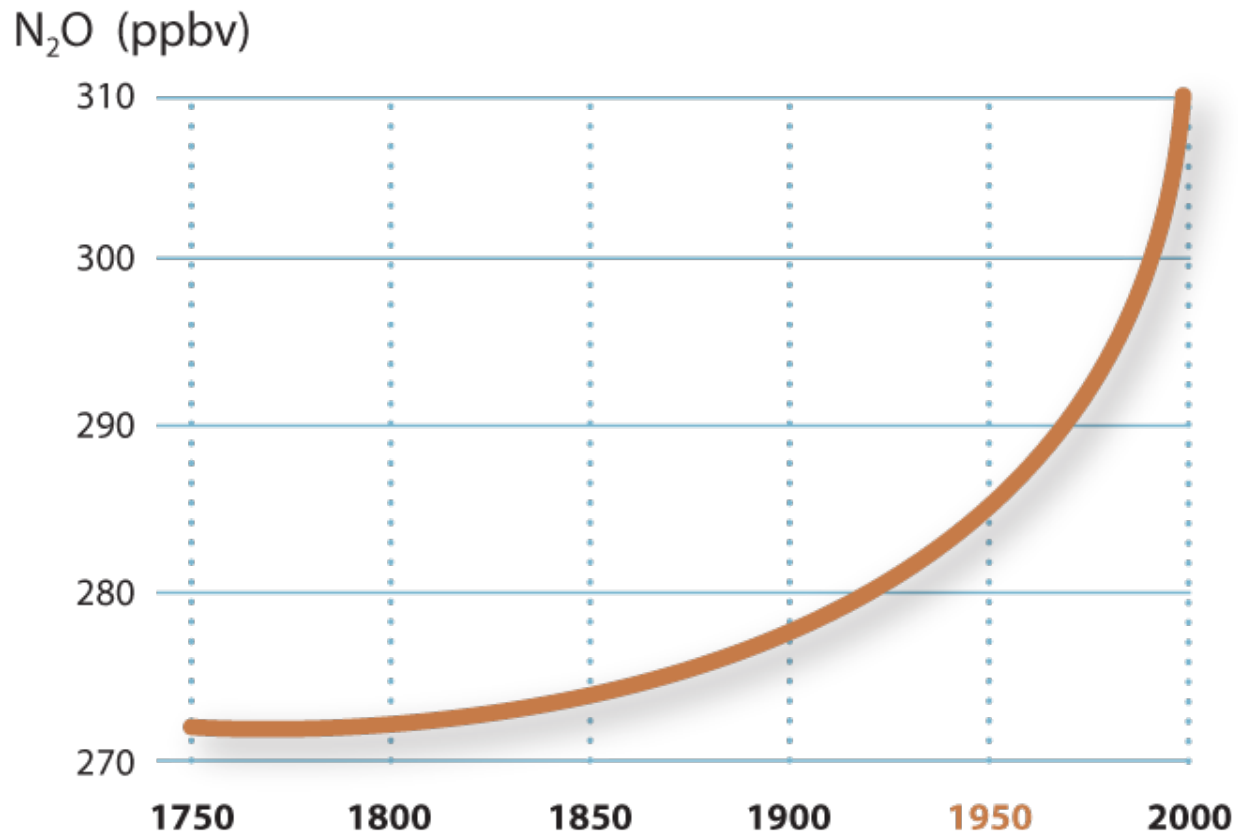
# Northern hemisphere average surface temperature



Mann et al Geophys Res Lett 26(6): 759-762

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

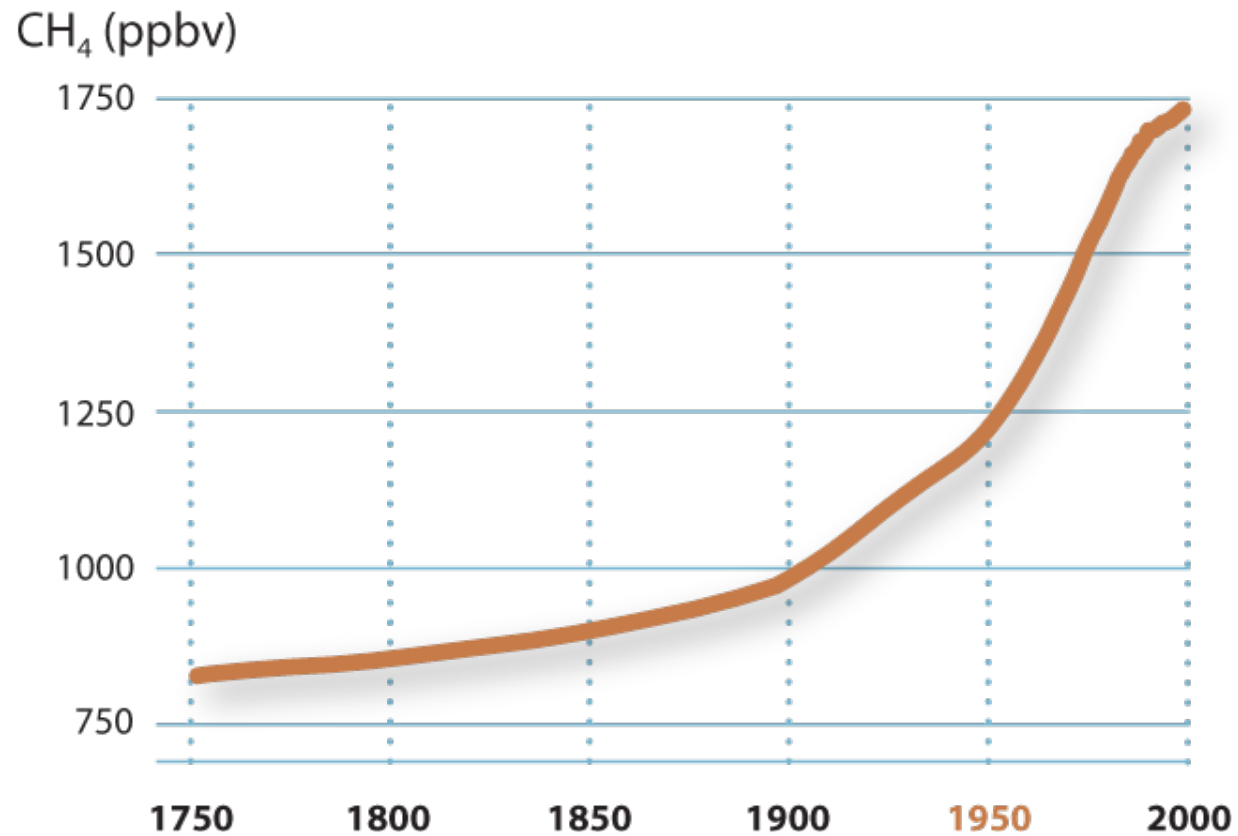
# Atmospheric N<sub>2</sub>O concentration



Machida et al Geophys Res Lett 22:2921-2925

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Atmospheric CH<sub>4</sub> concentration

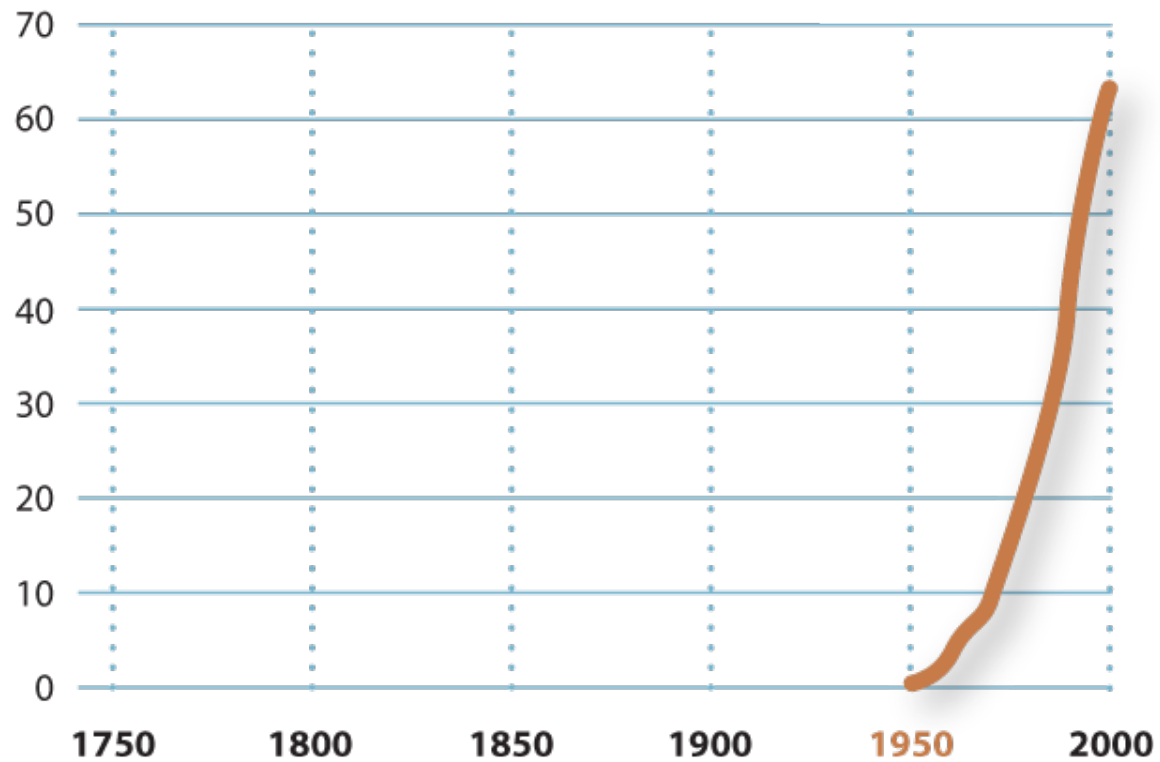


Blunier et al J Geophys Res 20: 2219-2222

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Ozone depletion

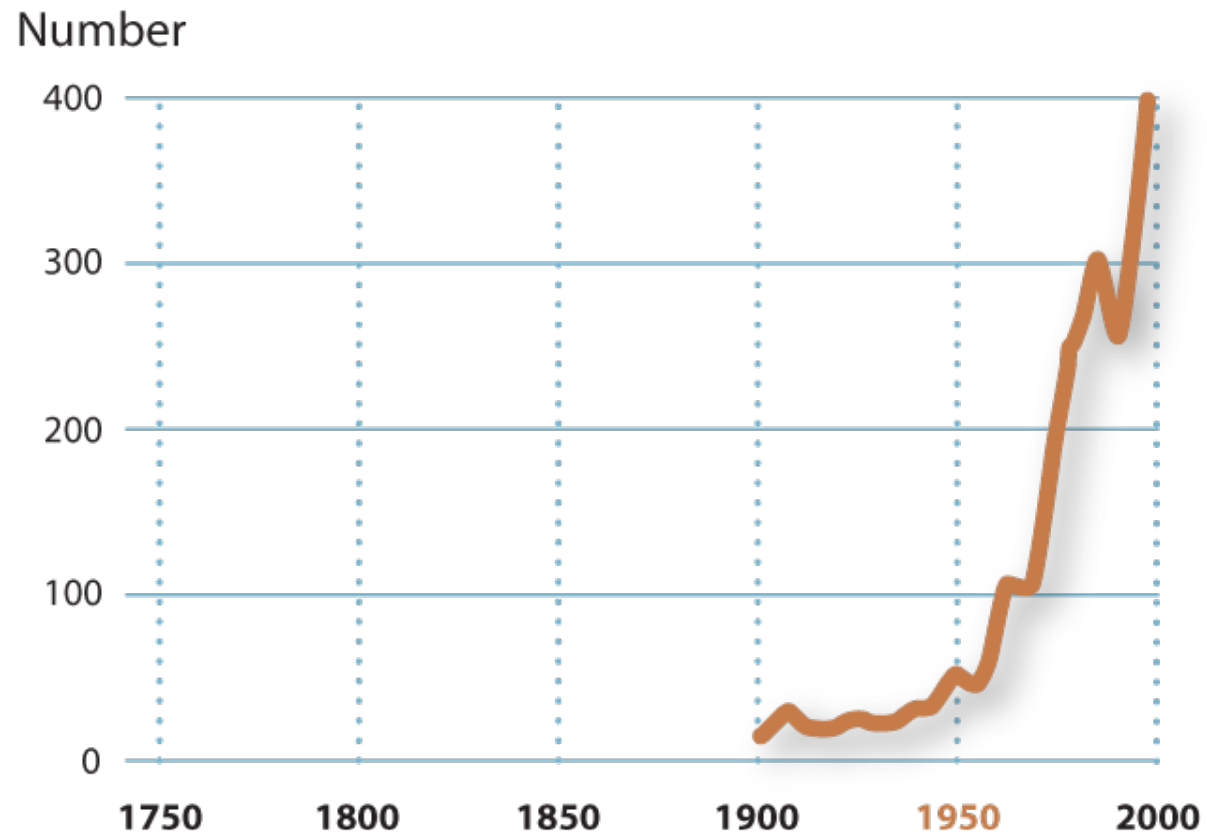
% loss of total column ozone



JD Shanklin British Antarctic Survey

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

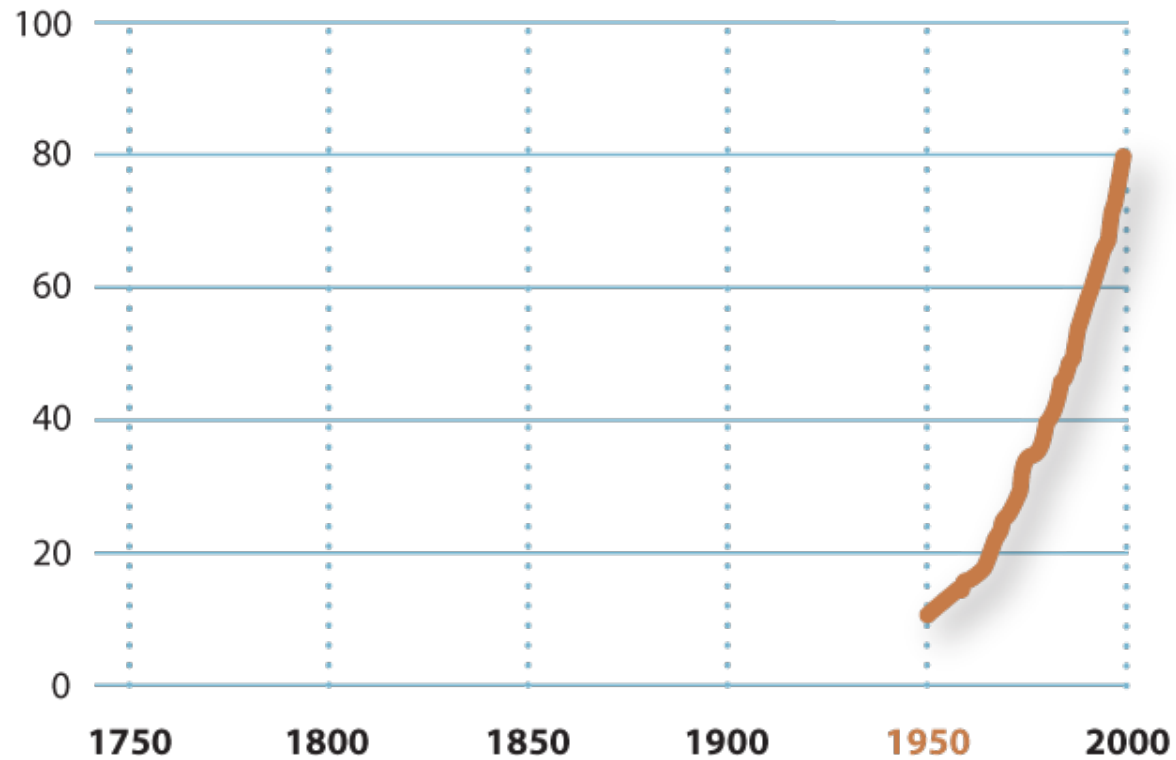
# Natural climactic disasters



IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Ocean ecosystems

% fisheries fully exploited



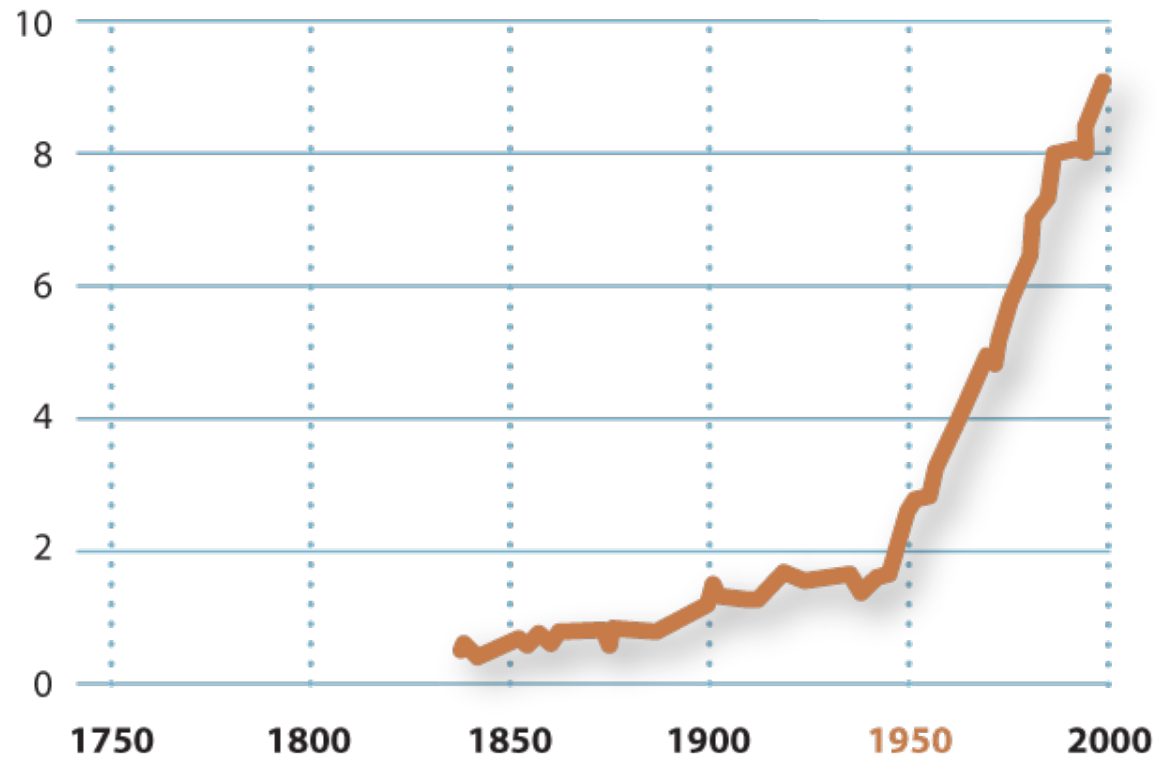
FAOSTAT 2002 Statistical database

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004



# Coastal zone nitrogen flux

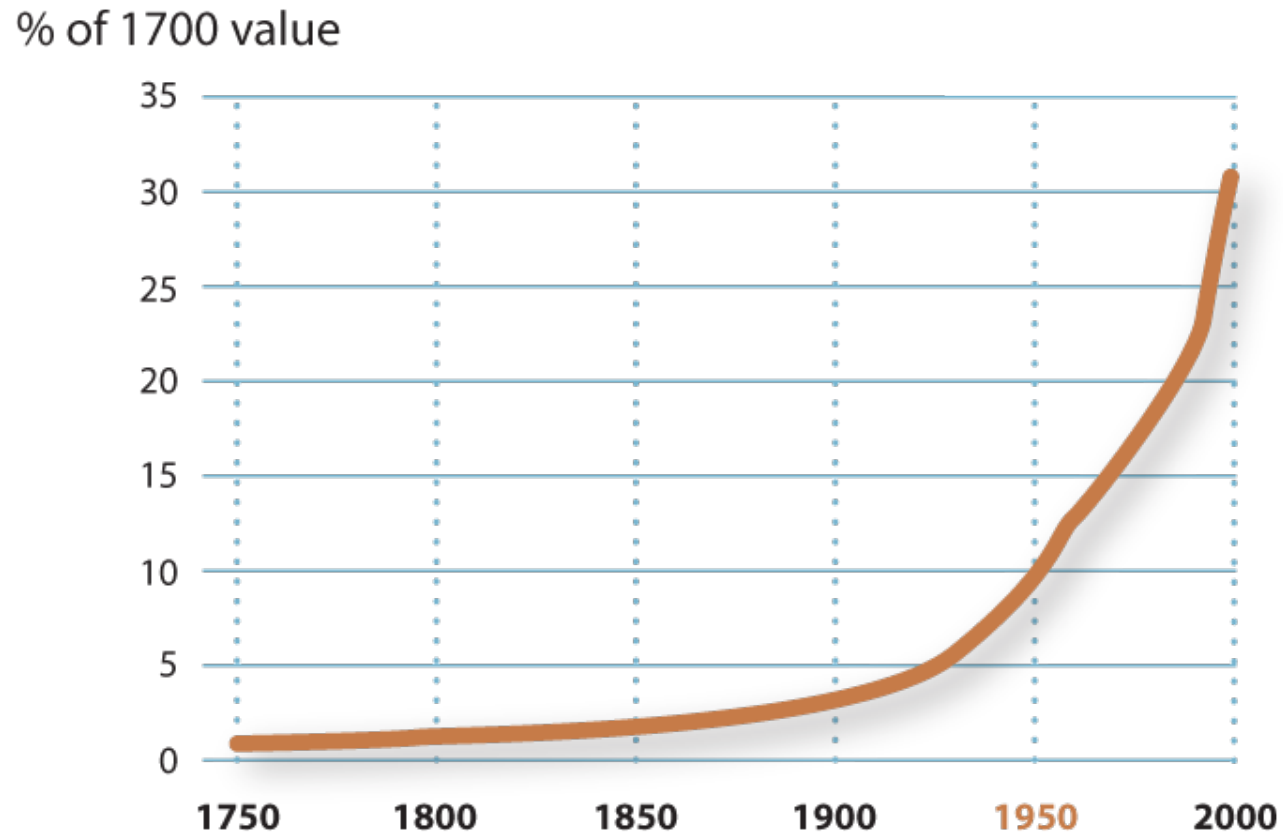
( $10^{12}$  moles year<sup>-1</sup>)



Mackenzie et al 2002.

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Tropical rainforest and woodland loss

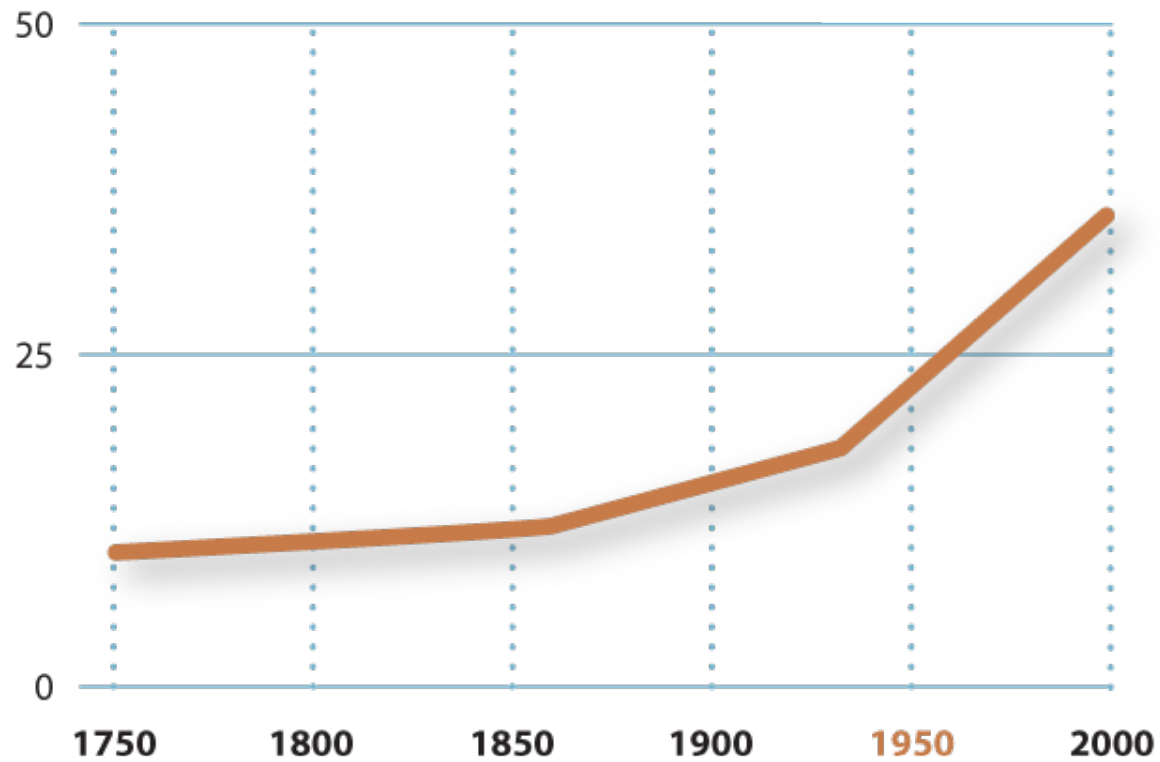


Richards, the Earth as transformed by human action, Cambridge University Press

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Domesticated land

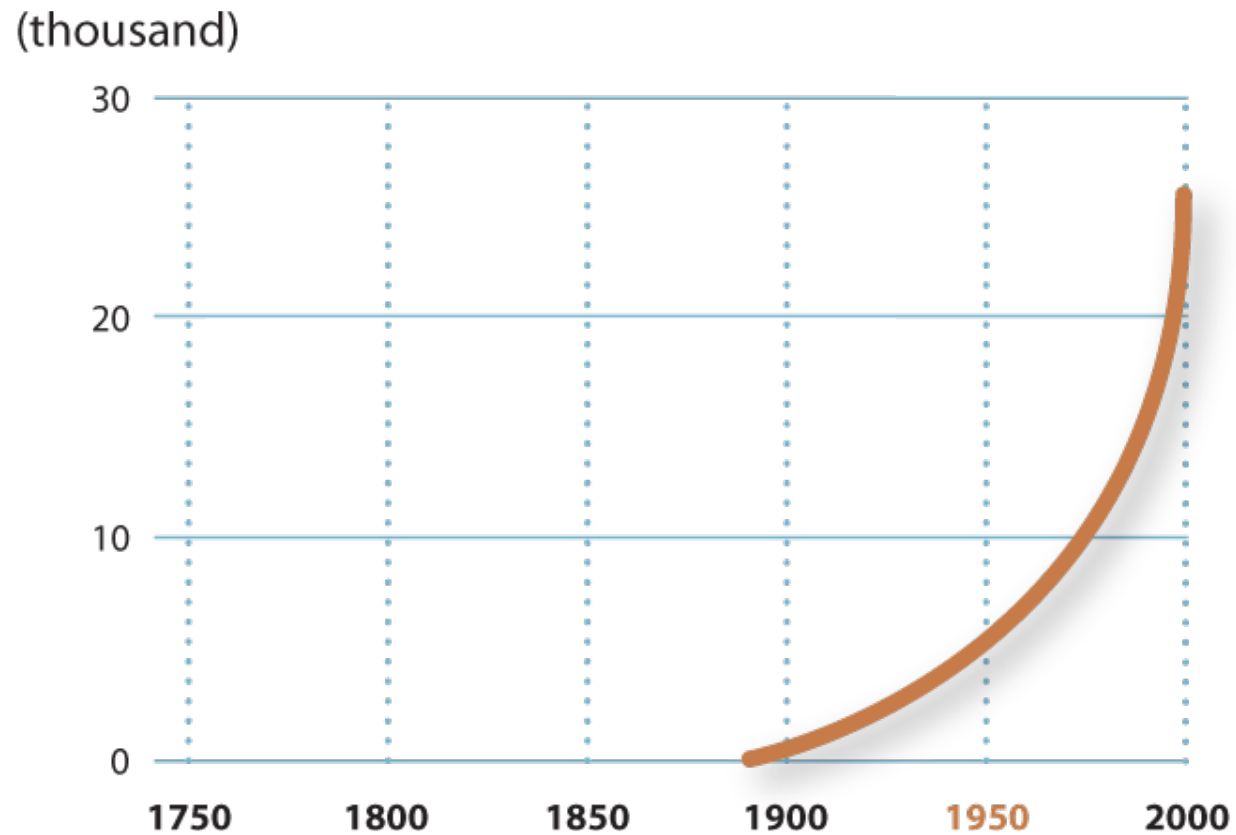
% of total land area



Klein Goldewijk and Battjes

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

# Species extinctions



Wilson, the Diversity of Life.

IGBP synthesis: Global Change and the Earth System, Steffen et al 2004

**CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>  
concentrations**

**Overfishing**

**Land degradation**

**Loss Biodiversity**

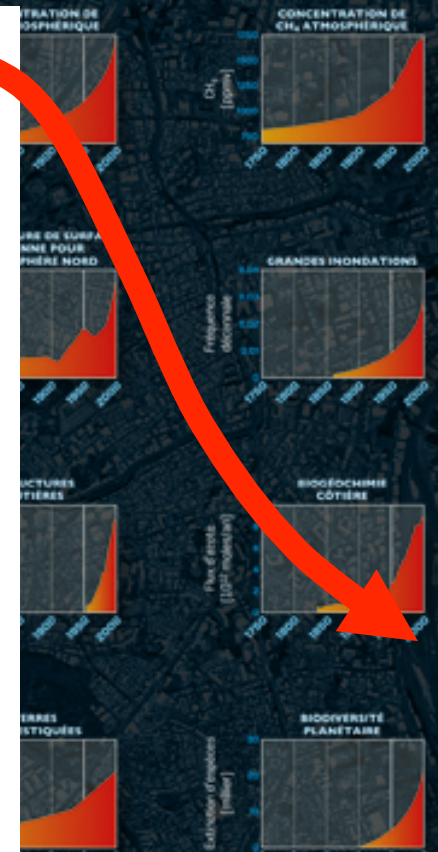
.....

1900

1950

2000

2010-2020



P x A x T = width times height times length of three boxes representing human impact in 1900, 1950 and 2011.

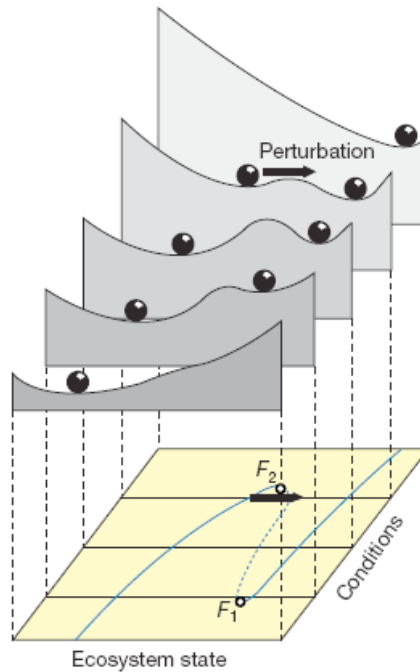
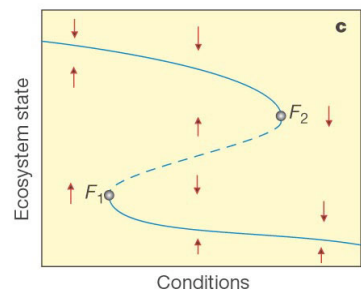
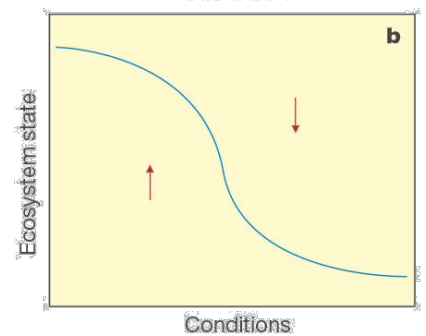
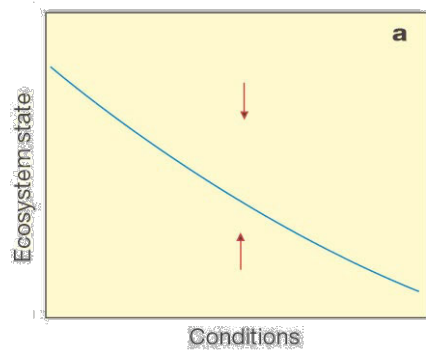


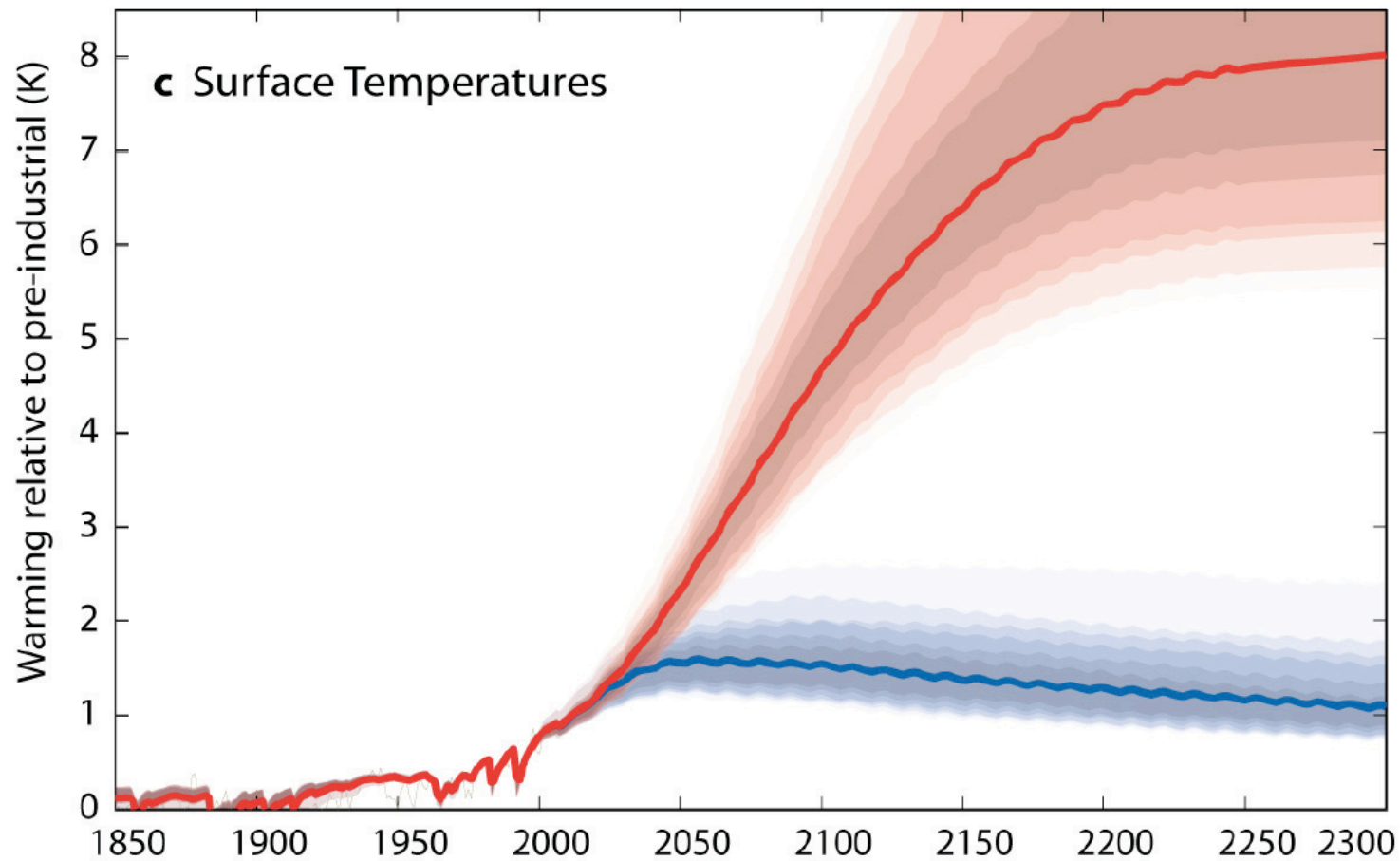
## 20th Century

Population	4X
Economic Output	22X
Fossil fuel consumption	14X

OECD Green Growth Report 2011

# Critical transitions or regime shifts



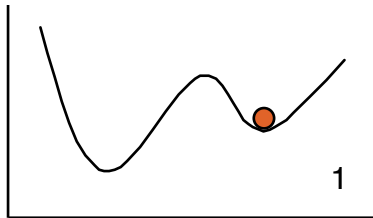
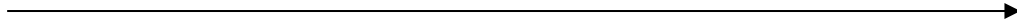


(Meinsheuzen et al., in prep)



# Valuable Ecosystem Services (Desirable)

# Loss of ecosystem services (Undesirable)



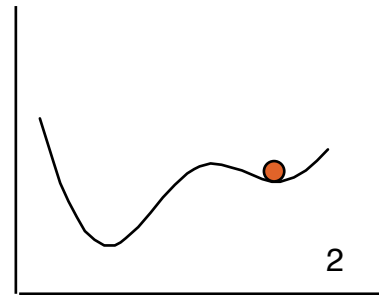
**coral dominance**



**clear water**



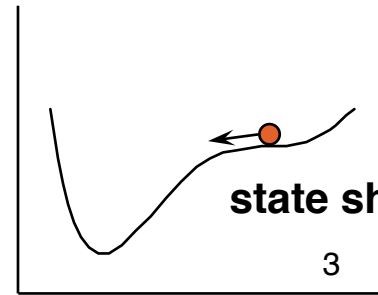
**grassland**



- overfishing, coastal eutrophication

- phosphorous accumulation in soil and mud

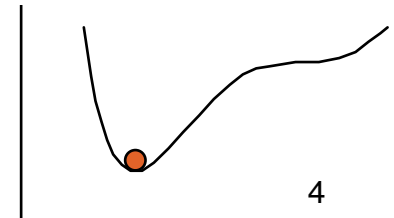
- fire prevention



- disease, hurricane

- flooding, warming, overexploitation of predators

- good rains, continuous heavy grazing



**algal dominance**



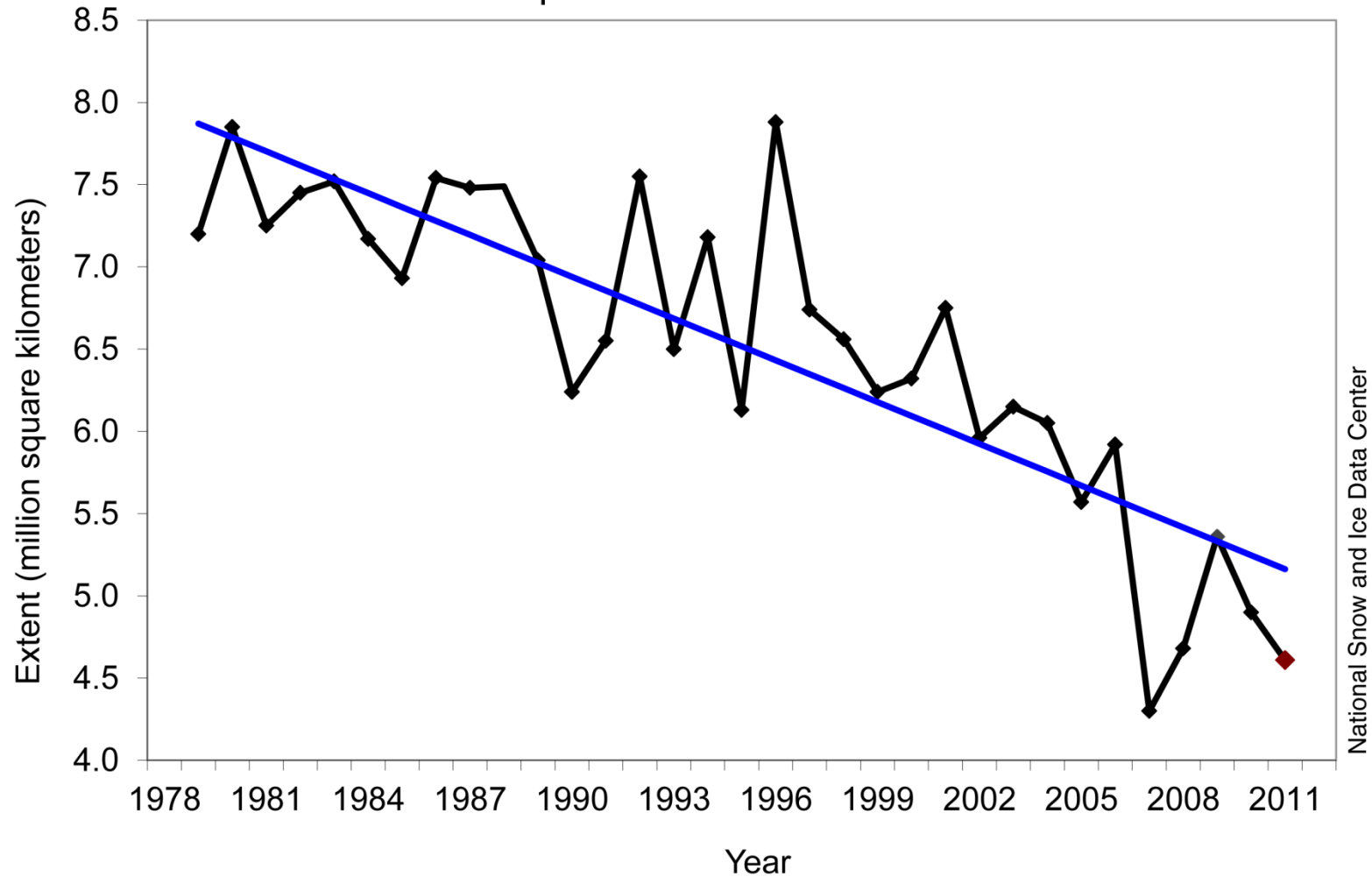
**turbid water**



**shrub-bushland**



## Average Monthly Arctic Sea Ice Extent September 1979 to 2011



# Reefs at risk revisited, 2011

- About 75 % of coral reefs threatened by local and global pressures.
- Climate change, ocean acidification, overfishing, destructive fishing, coastal development, and pollution.
- Since first Reefs at Risk in 1997 threats have increased on 30 % of reefs.
- Unless steps are taken threatened reefs will increase to more than 90 percent by 2030 and to nearly all reefs by 2050.

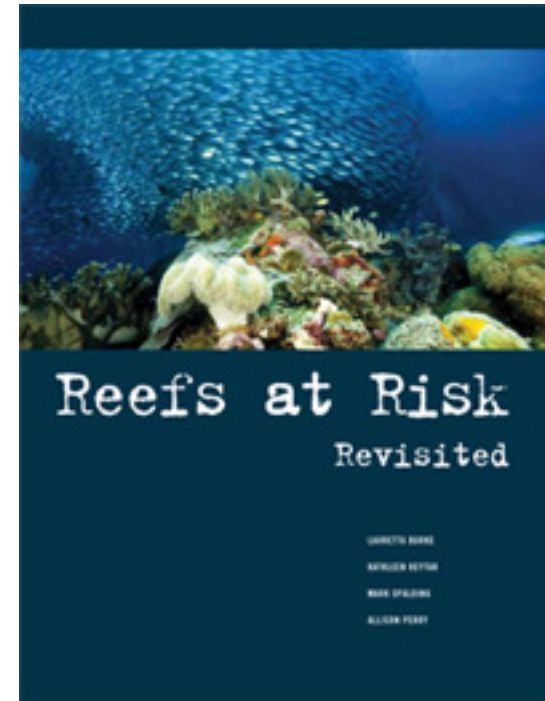






Photo: S Zeff / Azote



Photo: B Christensen / Azote

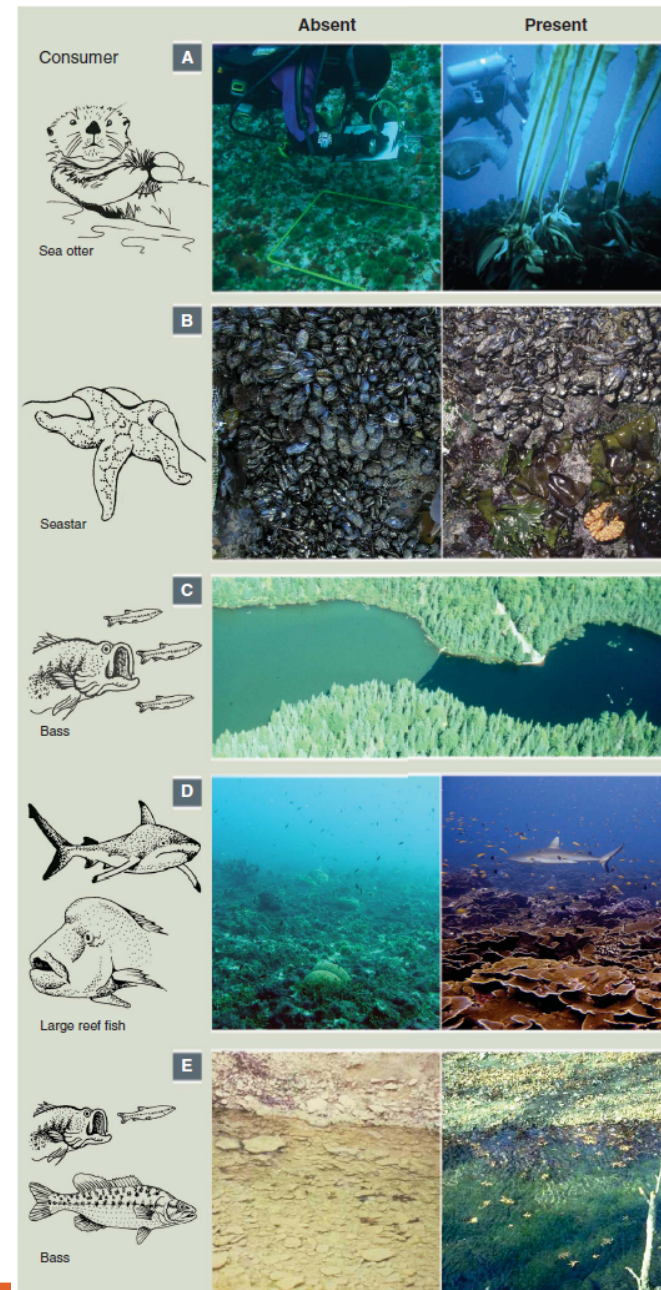


Photo: B Christensen / Azote

# Trophic Downgrading of Planet Earth

James A. Estes,<sup>1\*</sup> John Terborgh,<sup>2</sup> Justin S. Brashares,<sup>3</sup> Mary E. Power,<sup>4</sup> Joel Berger,<sup>5</sup> William J. Bond,<sup>6</sup> Stephen R. Carpenter,<sup>7</sup> Timothy E. Essington,<sup>8</sup> Robert D. Holt,<sup>9</sup> Jeremy B. C. Jackson,<sup>10</sup> Robert J. Marquis,<sup>11</sup> Lauri Oksanen,<sup>12</sup> Tarja Oksanen,<sup>13</sup> Robert T. Paine,<sup>14</sup> Ellen K. Pikitch,<sup>15</sup> William J. Ripple,<sup>16</sup> Stuart A. Sandin,<sup>10</sup> Marten Scheffer,<sup>17</sup> Thomas W. Schoener,<sup>18</sup> Jonathan B. Shurin,<sup>19</sup> Anthony R. E. Sinclair,<sup>20</sup> Michael E. Soulé,<sup>21</sup> Risto Virtanen,<sup>22</sup> David A. Wardle<sup>23</sup>

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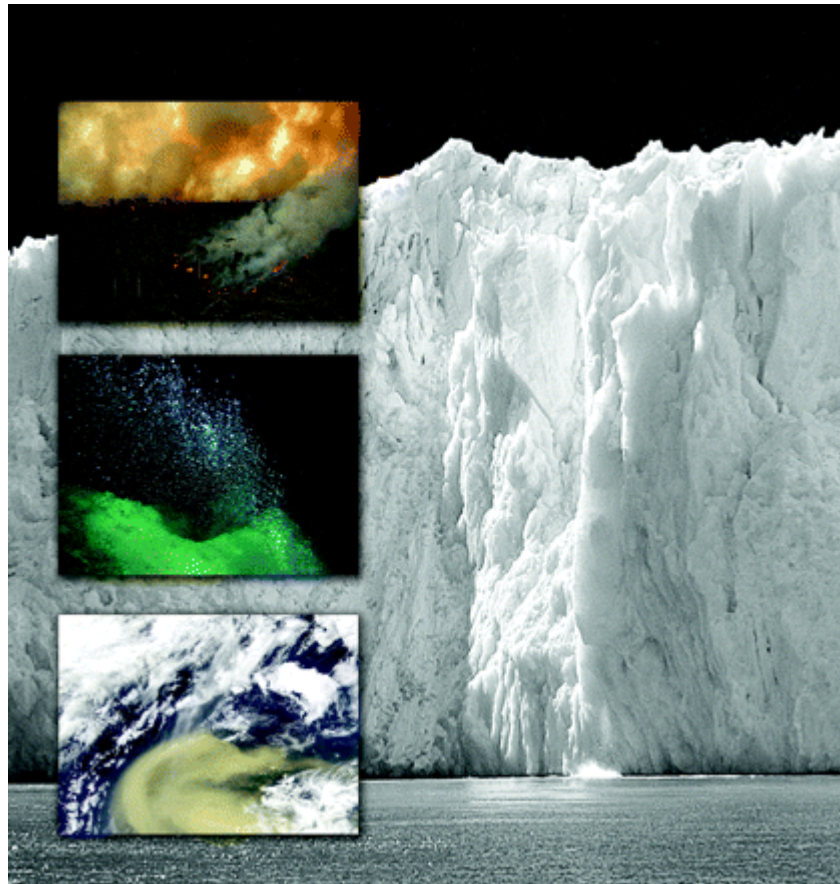
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# Tipping elements in the Earth system –

PNAS Special Feature released December 2009



PNAS Special Feature:  
Tipping elements in the Earth  
System, Jan 2010, vol 106 (49)

**Stockholm Resilience Centre**  
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Article

Will Steffen, Paul J. Crutzen and John R. McNeill

# The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?

Ambio Vol. 36, No. 8, December 2007



648

Review

TRENDS in Ecology and Evolution Vol.18 No.12 December 2003



## Catastrophic regime shifts in ecosystems: linking theory to observation

Marten Scheffer<sup>1</sup> and Stephen R. Carpenter<sup>2</sup>

<sup>1</sup>Department of Aquatic Ecology and Water Quality Management, Wageningen University, PO Box 8080, 6700 DD Wageningen, The Netherlands

<sup>2</sup>Center for Limnology, University of Wisconsin, 680 North Park Street, Madison, WI 53706, USA

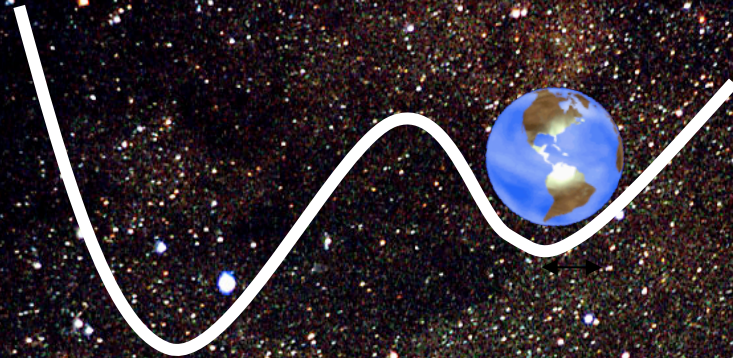
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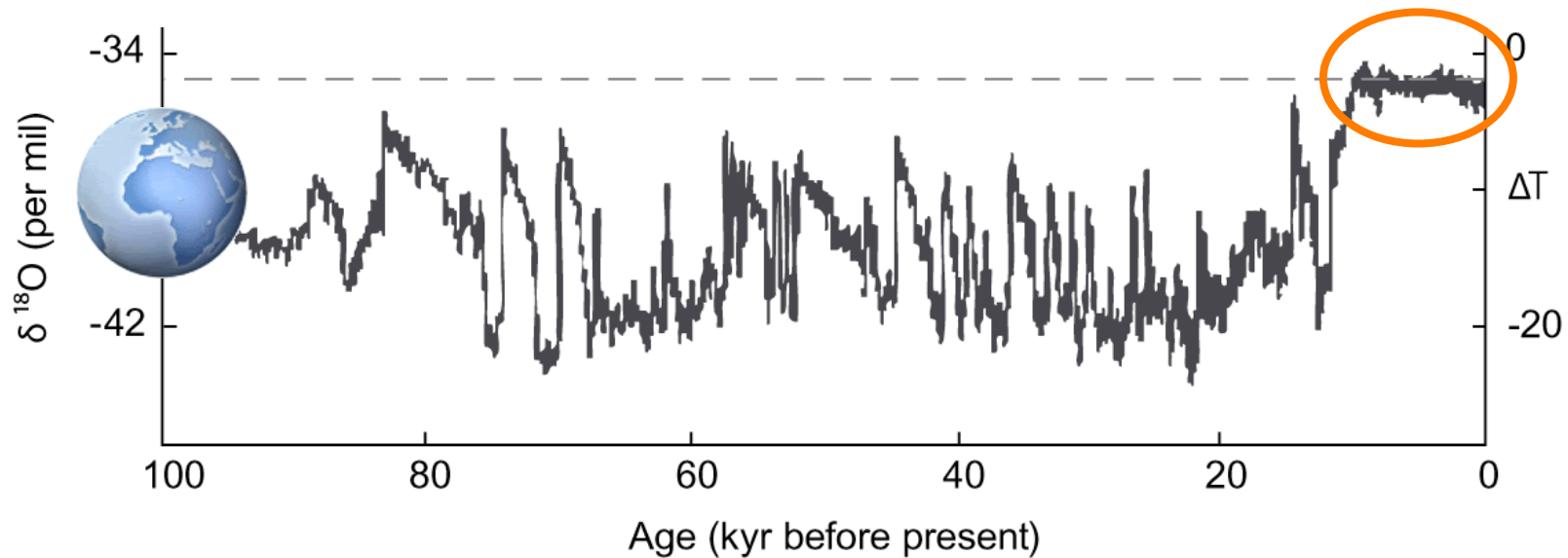
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# The Resilience of the Earth System



# Humanity's 10,000 years of grace



# Transgressing safe boundaries

**nature**  
**FEATURE**  
**A safe operating space for humanity**  
 Identifying and quantifying planetary boundaries that must not be transgressed could help prevent human activities from causing unacceptable environmental change, argue **Johan Rockström** and colleagues.

Although Earth has undergone many periods of significant environmental change, the planet's environment has been unusually stable for the past 10,000 years<sup>1</sup>. This period of stability — known as the Holocene — has seen human civilisations arise, develop and thrive. Such stability may now be under threat. Since the Industrial Revolution, a new era has arisen: the Anthropocene, in which human actions have become the main driver of global environmental change<sup>2</sup>. This could see human activities push the Earth system outside stable environmental states that are detrimental or with consequences for large parts of the world even catastrophic for large parts of the world.

During the Holocene, environmental change occurred naturally and the conditions largely capacity maintained the conditions that enabled human development. Despite that, freshwater availability and temperatures have all stayed within a relatively narrow range. Now, largely because of a rapidly growing reliance on fossil fuels and



**SUMMARY**

- New approach proposed for defining preconditions for human development
- Crossing certain biophysical thresholds could have disastrous consequences for humanity
- Three of nine interlinked planetary boundaries have already been overstepped

Industrialized forms of agriculture, human activities have reached a level that could damage the systems that keep Earth in the desirable Holocene state. The result could be irreversible and, in some cases, always less conducive to change, leading to a state less conducive to human development<sup>3</sup>. Without pressure from humans, the Holocene is expected to continue for at least several thousands of years<sup>4</sup>.

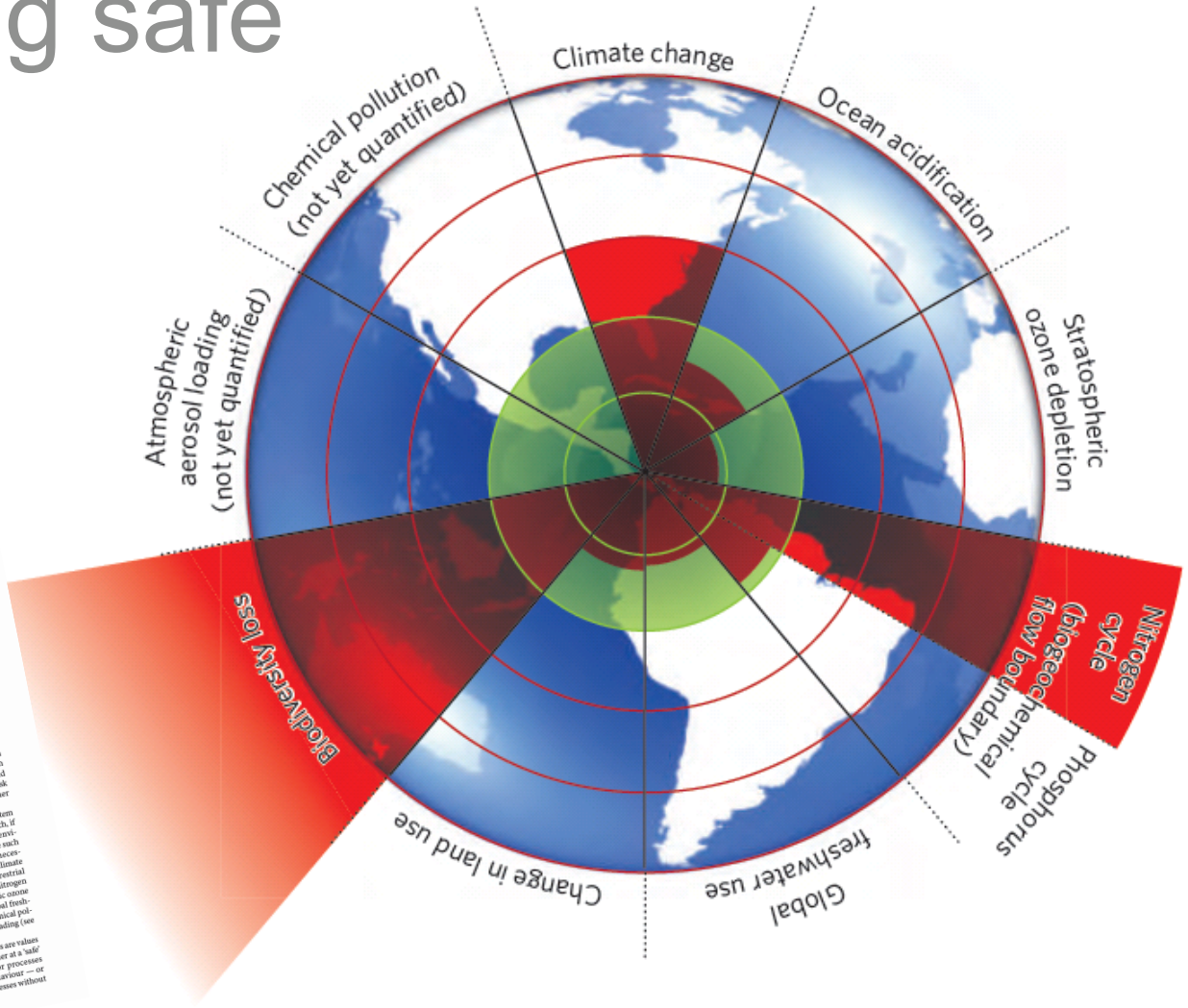
**Planetary boundaries**  
 To meet the challenge of maintaining the Holocene state, we propose a framework based on 'planetary boundaries'. These boundaries define the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems or processes. Although Earth's complex systems sometimes respond smoothly to changing pressures, it seems that this will prove to be the exception rather than the rule. Many subsystems of Earth react in a nonlinear, often abrupt, way, and are particularly sensitive around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a monsoon system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humans<sup>5</sup>.

Most of these thresholds could be defined by a critical value for one or more control variables, such as carbon dioxide concentration. Six of the processes or subsystems on Earth have well-defined thresholds, although human actions that undermine the resilience of such processes or subsystems — for example, land and water degradation — can increase the risk that thresholds will also be crossed in other processes, such as the climate system.

We have tried to identify the Earth-system processes and associated thresholds which, if crossed, could generate unacceptable environmental change. We have found nine such processes for which we believe it is necessary to define planetary boundaries: climate change; rate of biodiversity loss (terrestrial and marine); interference with the nitrogen and phosphorus cycles; stratospheric ozone depletion; ocean acidification; global freshwater use; change in land use; chemical pollution; and atmospheric aerosol loading (see Fig. 1 and Table).

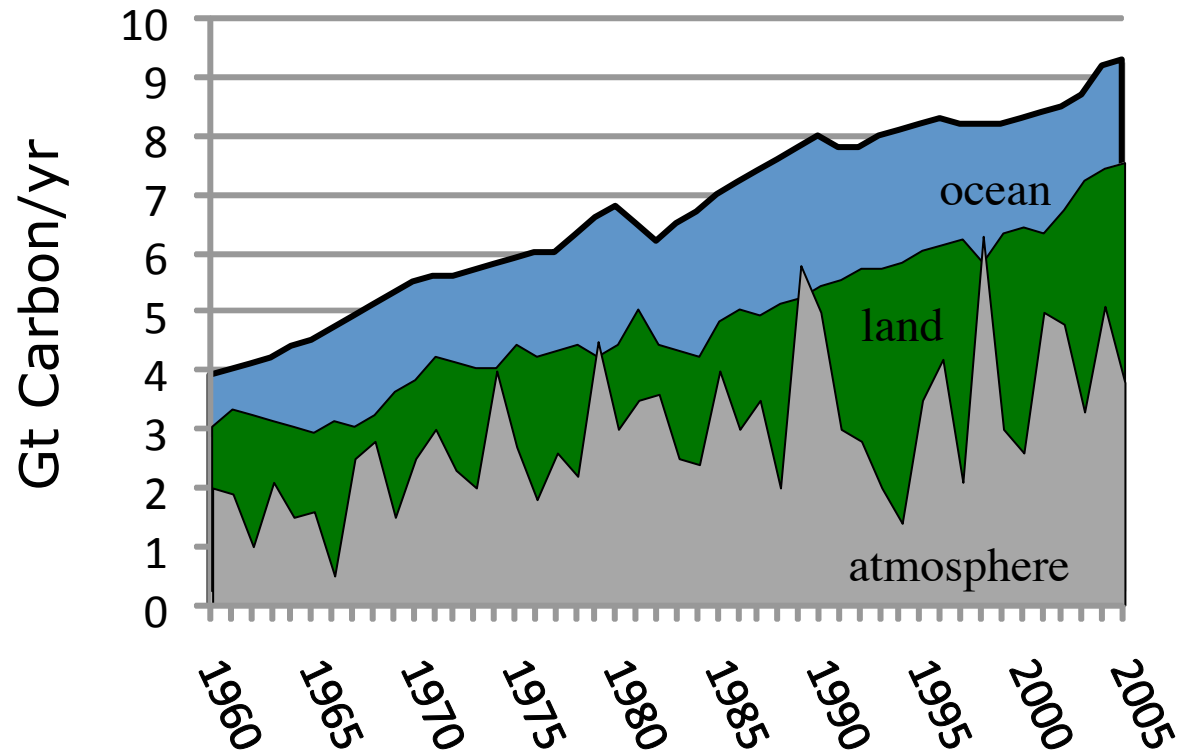
Fig. 1 and Table). In general, planetary boundaries are values for control variables that are either at a safe distance from thresholds — for processes with evidence of threshold behaviour — or at dangerous levels — for processes without

**Figure 1 | Beyond the boundaries.** The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in these systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.  
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Rockström et al. 2009 Nature, 461 (24): 472-475

# Biosphere interactions with the climate system



Adapted from Canadell et al., 2007

# Earth System Science for Global Sustainability: Grand Challenges

W. V. Reid,<sup>1\*</sup> D. Chen,<sup>2</sup> L. Goldfarb,<sup>2</sup> H. Hackmann,<sup>3</sup> Y. T. Lee,<sup>2</sup> K. Mokhele,<sup>4</sup> E. Ostrom,<sup>5</sup> K. Raivio,<sup>2</sup> J. Rockström,<sup>6</sup> H. J. Schellnhuber,<sup>7</sup> A. Whyte<sup>8</sup>

Progress in understanding and addressing both global environmental change and sustainable development requires better integration of social science research.

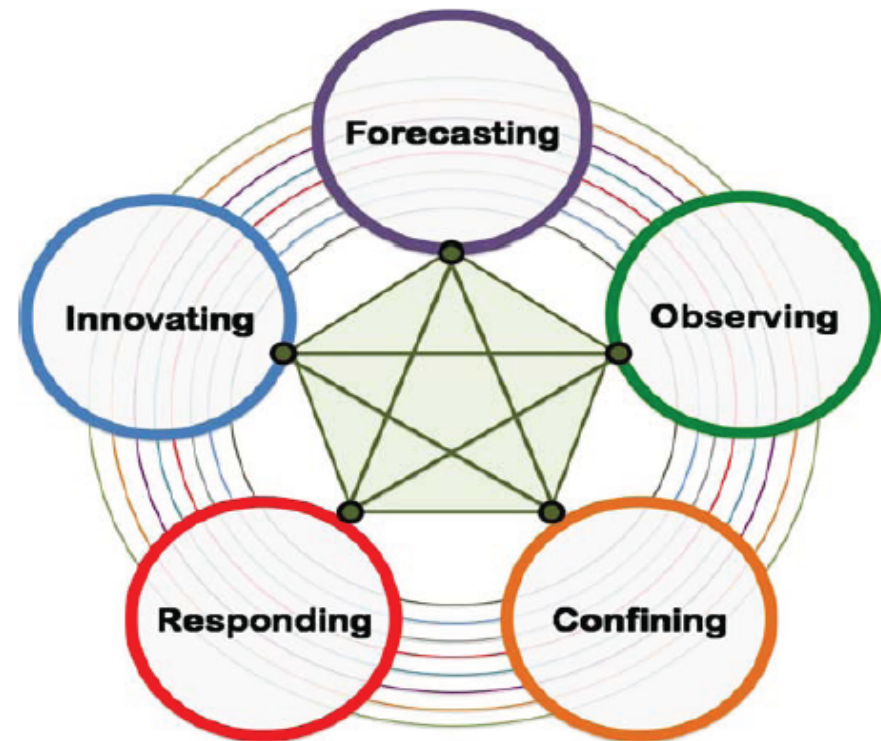
12 NOVEMBER 2010 VOL 330 SCIENCE [www.sciencemag.org](http://www.sciencemag.org)  
Published by AAAS

Global sustainability now a prerequisite for Poverty Alleviation

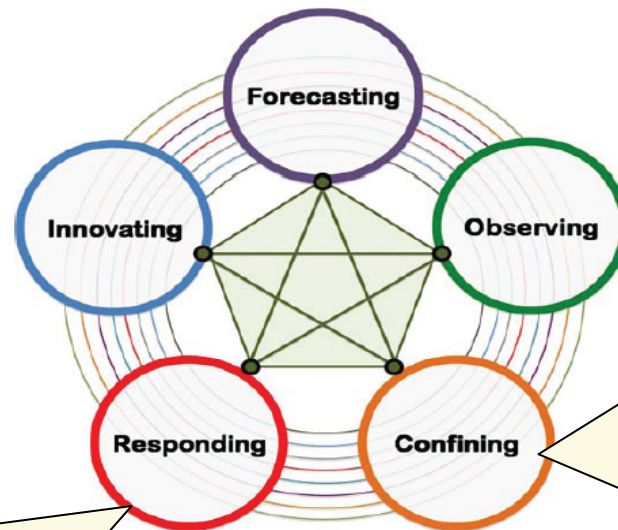
Predict risks of catastrophic thresholds in the Earth system

Innovation pathways for a Grand Transformation to global sustainability

Planetary Stewardship for human prosperity in the Anthropocene



What significant environmental changes are likely to result from human actions? How would those changes affect human well-being, and how are people likely to respond?



How can the need to curb global environmental change be integrated with the demands of other inter-connected global policy challenges, particularly those related to poverty, conflict, justice and human security?

What strategies for avoidance, adaptation and transformation are effective for coping with abrupt changes, including massive cascading environmental shocks?



# A global Alliance for a new 10-year initiative



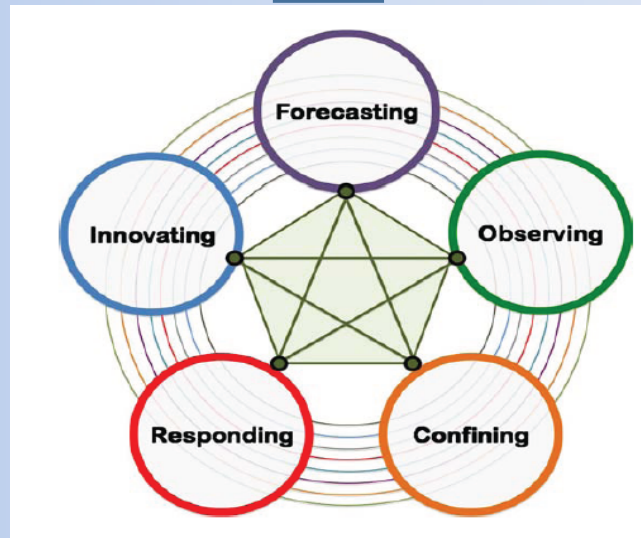
Note: WMO is an observer to ESSI

5-10 Grand Questions  
Humanity needs answered for a successful transition to global sustainability

Strategic principles for research

- integration Nat-Soc sciences
- cross-scale interactions
- Broad stakeholder engagement
- contribute to transitions toward global sustainability
- Engaging young scientists from N and S
- Set boundary on Earth system research for global sustainability

Research Framework guided by an integration of Grand Challenge Research questions and Belmont White paper



RESEARCH FRAMEWORK GUIDING → GOVERNANCE FRAMEWORK

Unified Governing framework

Guided by Common Research framework

Organisation and Network structure able to deliver on Research framework

*Global Support*  
SYNTHESIS  
ASSESSMENT  
CAPACITY DEVELOPMENT  
SERVICES/IMPACT  
COMMUNICATIONS

- 
- Alliance of science, funders with one common research framework (Grand Challenges and Belmont Challenge)
  - Co-design and trans-disciplinary endeavour – integrating sciences, integrating science-policy-practice
  - Guided by common research strategy
  - Governed by one unified governance framework
  - Invest in global network and knowledge nodes
  - Generate global scientific enthusiasm – a common global challenge
  - Major investment in joint "business plan" for IMPACT, SYNTHESIS, ASSESSMENT, CAPACITY DEVELOPMENT, COMMUNICATIONS, AND RESOURCES

# The Earth System Sustainability Initiative:

Earth System Research

## ”Future Earth”

for Sustainable Development

Science for  
Global  
Sustainability

**INSIGHTS**

**SOLUTIONS**

**SYNTHESIS**

**ASSESSMENT**

**IMPACT**

**SERVICES**

**CAPACITIES**

**AWARENESS**

Climate dynamics

Global Earth Observations

Land-ocean interactions

Cryosphere dynamics

Global N and P cycles

Global Water systems

Earth system governance

Vulnerability, Resilience

Human dimensions

Growth and Sustainability

Earth system modelling

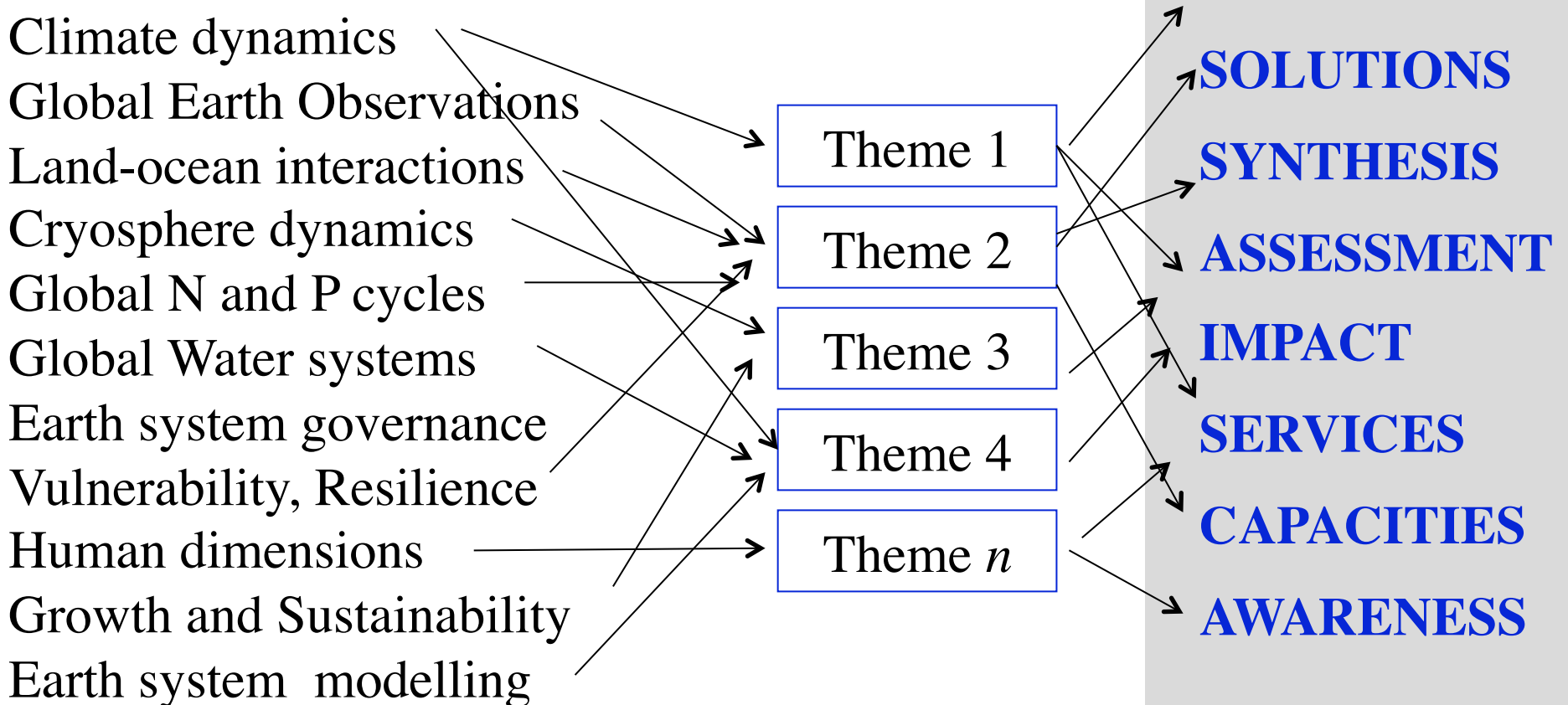
Theme 1

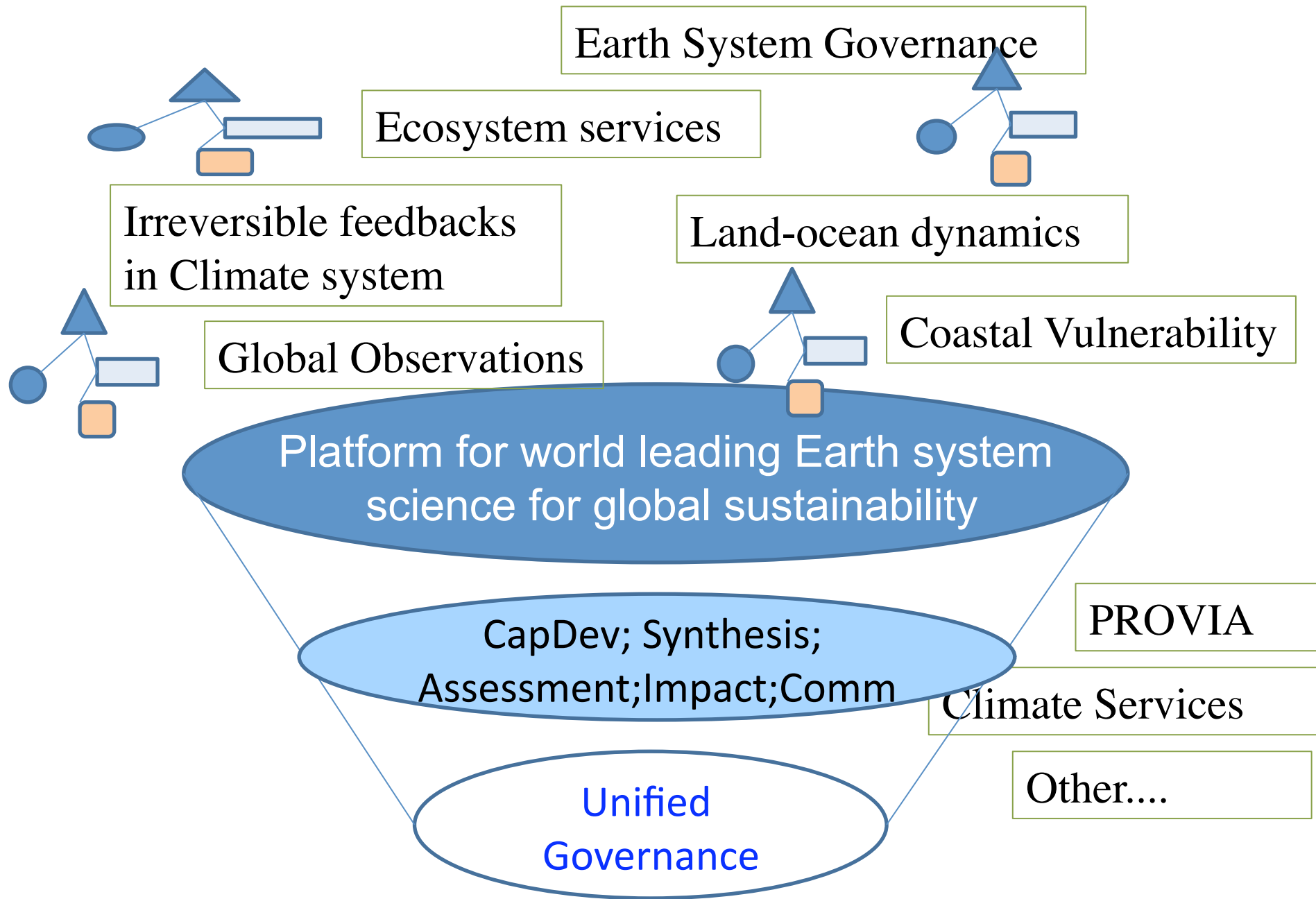
Theme 2

Theme 3

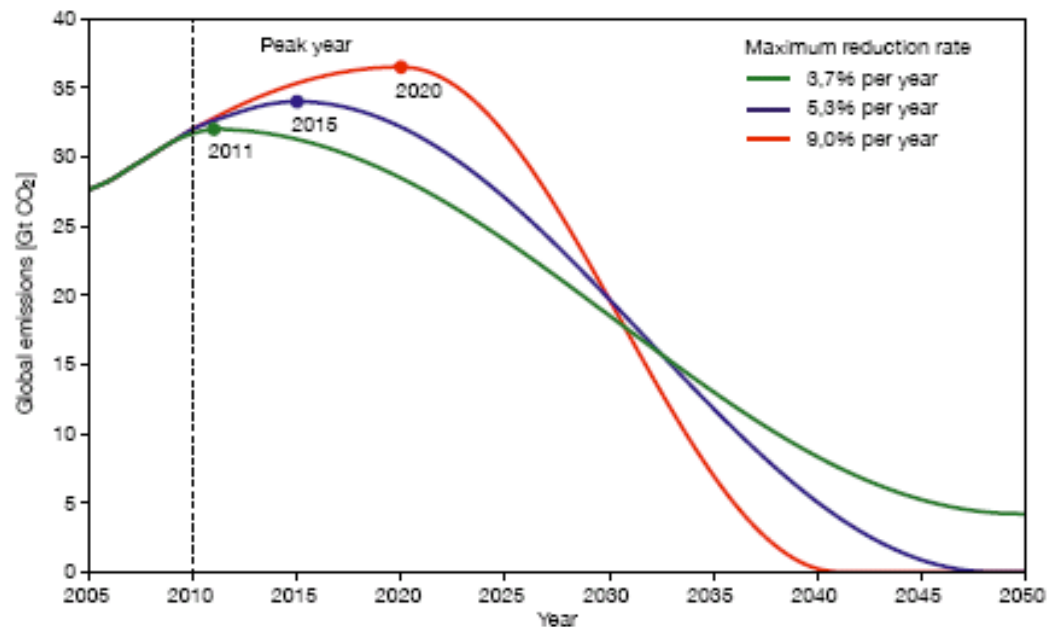
Theme 4

Theme *n*





# RESPONSE: Climate science; global governance; innovation pathways;



**Figure 3.2-1**

Examples of global emission pathways for the period 2010–2050 with global CO<sub>2</sub> emissions capped at 750 Gt during this period. At this level, there is a 67% probability of achieving compliance with the 2°C guard rail (Chapter 5). The figure shows variants of a global emissions trend with different peak years: 2011 (green), 2015 (blue) and 2020 (red). In order to achieve compliance with these curves, annual reduction rates of 3.7% (green), 5.3% (blue) or 9.0% (red) would be required in the early 2030s (relative to 2008).

Source: WBGU

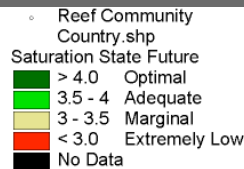
(WBGU 2009)

# OBSERVATION + RESPONSE:

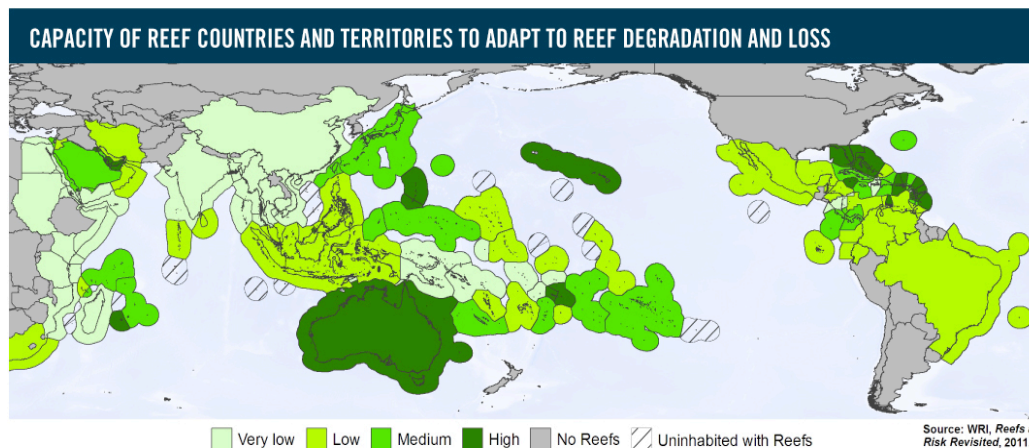
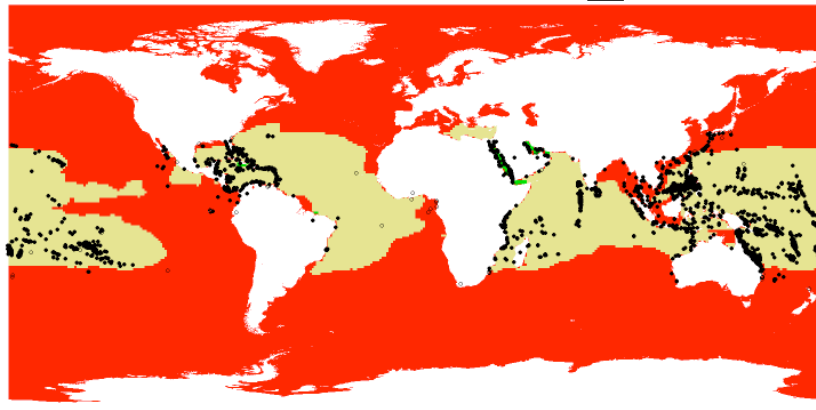
Ocean tipping points and marine stewardship

Coastal vulnerability – how far will adaptation take us?

Ocean Aragonite Saturation State



References: 5, 7



Notes: Adaptive capacity is based on economic resources, education, health, governance, access to markets, and agricultural resources. Eighty-one countries, 21 island territories, and six subnational regions (Florida, Hawaii, Hong Kong SAR, Peninsular Malaysia, Sabah, and Sarawak) were assessed, and are categorized according to quartiles.

Ocean  
Acidification  
And capacity  
for adaptive  
Coral Reef  
management

# CONFINING+OBSERVING+RESPONSE : Forest and Land use management to sustain global carbon sinks in the biosphere

## A Large and Persistent Carbon Sink in the World's Forests

Yude Pan,<sup>1\*</sup> Richard A. Birdsey,<sup>1</sup> Jingyun Fang,<sup>2,3</sup> Richard Houghton,<sup>4</sup> Pekka E. Kauppi,<sup>5</sup> Werner A. Kurz,<sup>6</sup> Oliver L. Phillips,<sup>7</sup> Anatoly Shvidenko,<sup>8</sup> Simon L. Lewis,<sup>7</sup> Josep G. Canadell,<sup>9</sup> Philippe Ciais,<sup>10</sup> Robert B. Jackson,<sup>11</sup> Stephen W. Pacala,<sup>12</sup> A. David McGuire,<sup>13</sup> Shilong Piao,<sup>2</sup> Aapo Rautiainen,<sup>5</sup> Stephen Sitch,<sup>7</sup> Daniel Hayes<sup>14</sup>

19 AUGUST 2011 VOL 333 SCIENCE www.sciencemag.org

Total Forest Sink  
 $2,4 \pm 0,4 \text{ Pg C yr}^{-1}$

Total Forest Source  
 $1,3 \pm 0,5 \text{ Pg C yr}^{-1}$

Net Forest Sink  
 $1,1 \pm 0,8 \text{ Pg C yr}^{-1}$

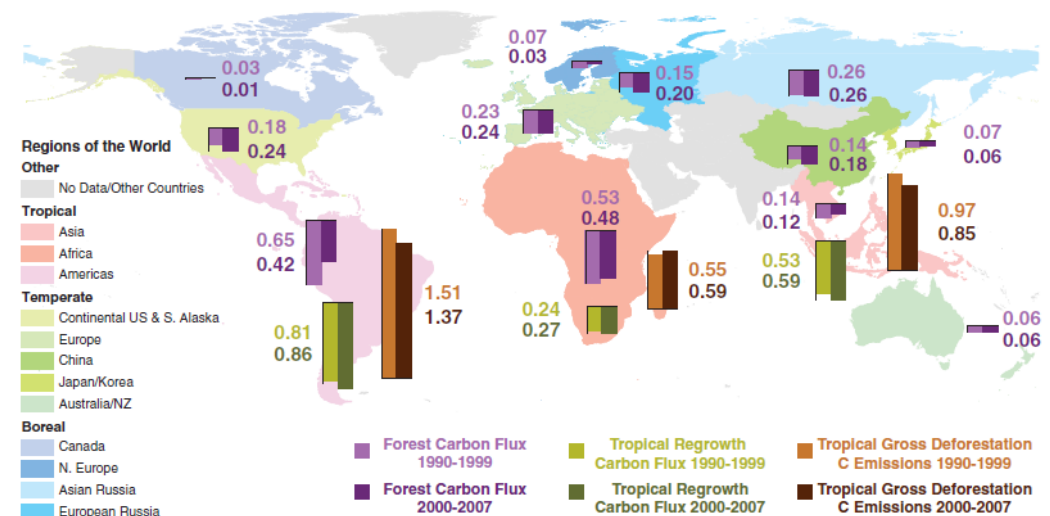
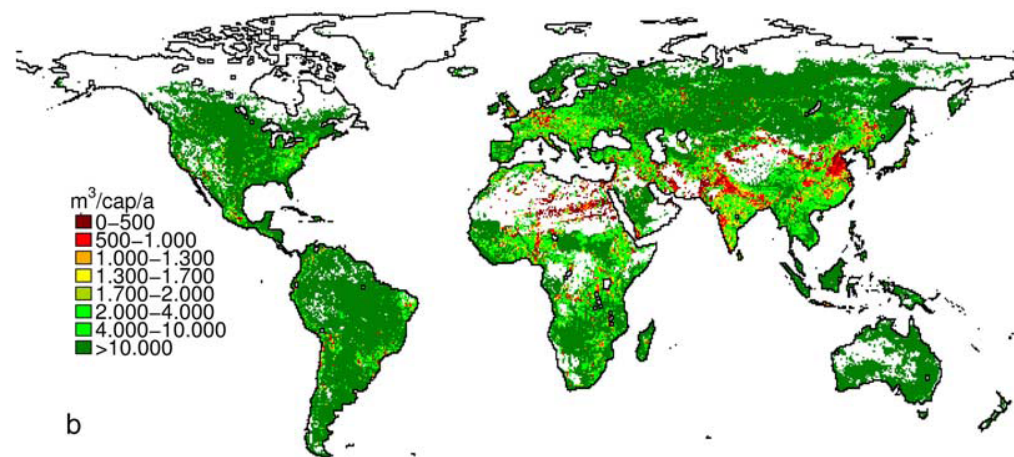
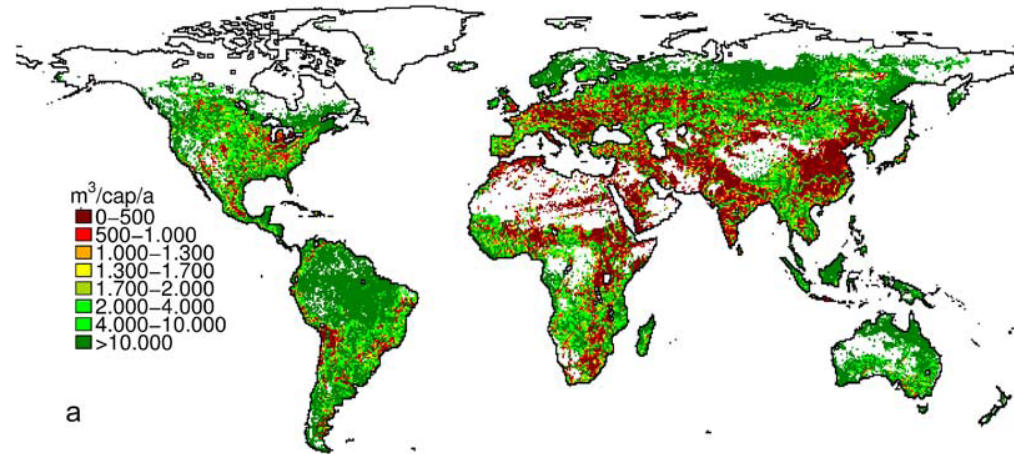
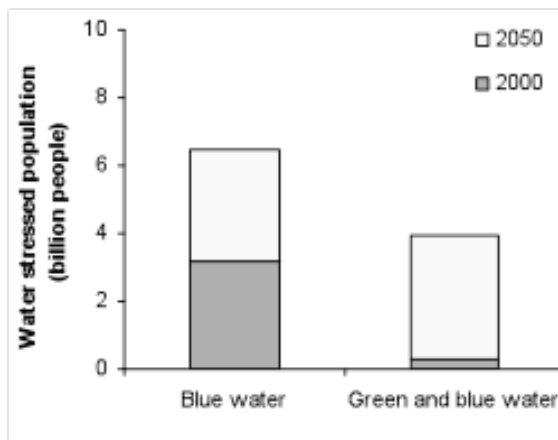


Fig. 1. Carbon sinks and sources ( $\text{Pg C year}^{-1}$ ) in the world's forests. Colored bars in the down-facing direction represent C sinks, whereas bars in the upward-facing direction represent C sources. Light and dark purple, global established forests (boreal, temperate, and intact tropical forests); light and dark green, tropical regrowth forests after anthropogenic disturbances; and light and dark brown, tropical gross deforestation emissions.



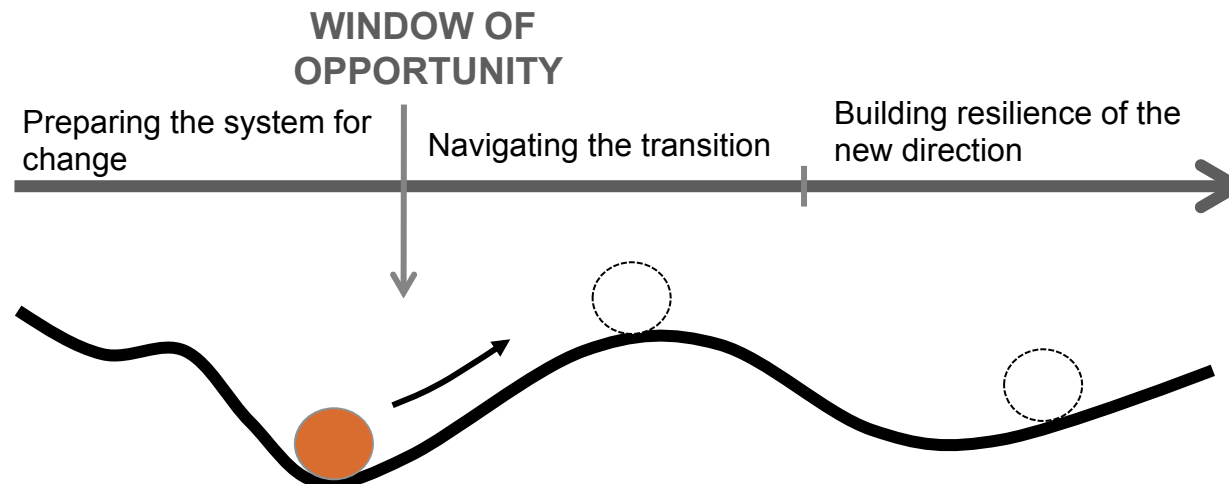
# FORECAST + CONFINE : Global freshwater security and moisture feedback over continents under climate change scenarios

## Changing the Face of Water Scarcity



Rockström et al., 2009. Water Resources Research

# RESPONSE AND INNOVATION: Turning crisis into opportunity A shift in mindset for transformation



# FORECAST & RESPONSE

## Tipping toward global sustainability

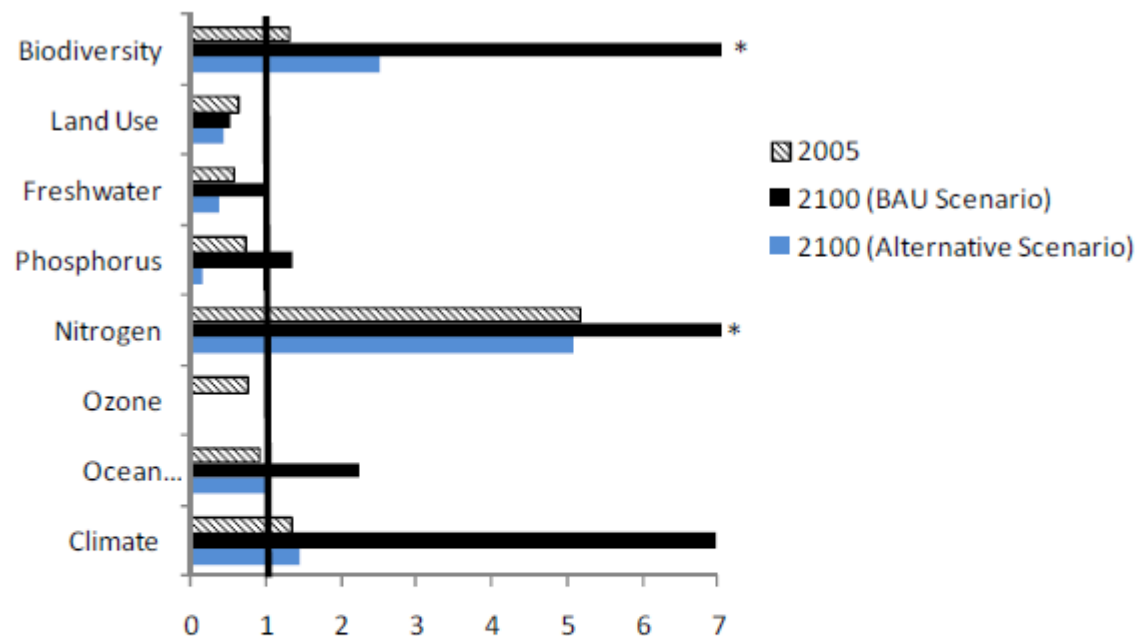
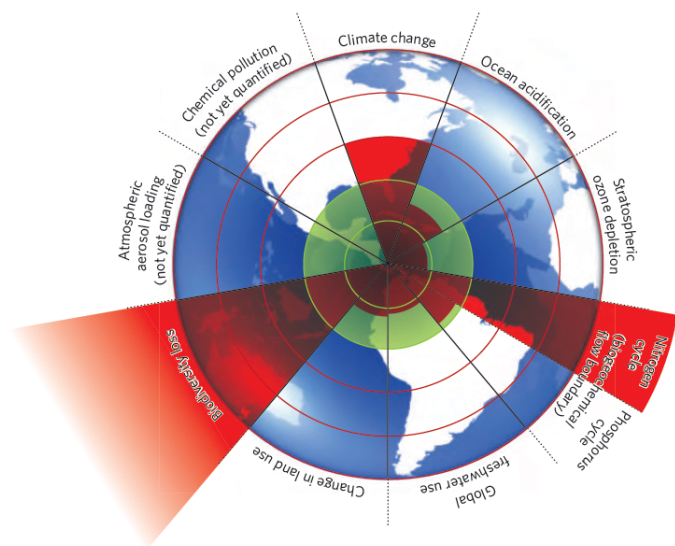
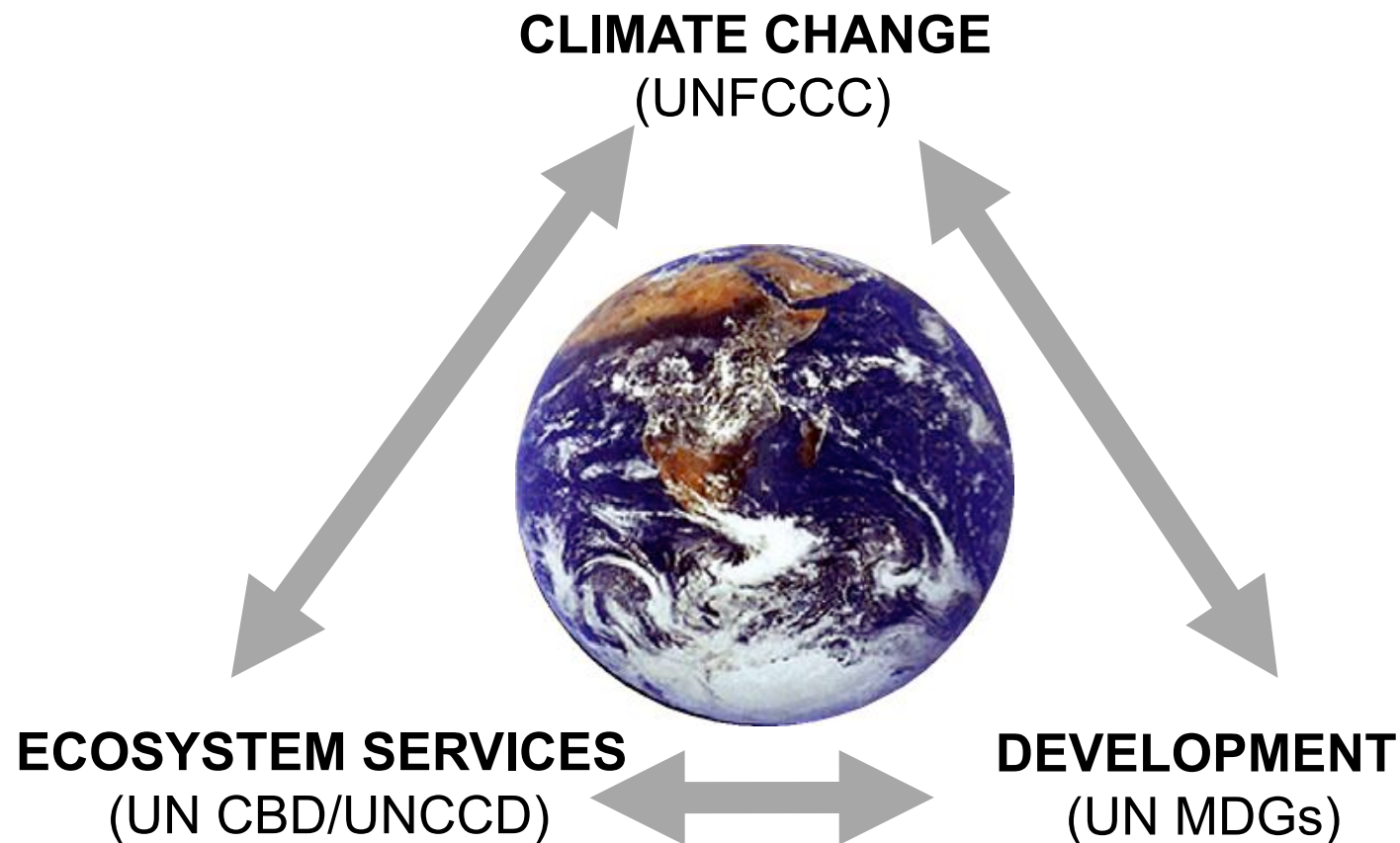


Figure 13. Planetary Boundaries. Horizontal axis is normalized so that a value below one indicates operation within Earth's safe operating space. \* indicates values too large to display on chart (Biodiversity = 14 and Nitrogen = 11.5).

Tellus, 2011, draft for Ban Ki-moon high level panel

# RESPONDING: Integrating planetary efforts for human development



ECOLOGY

# The Biodiversity and Ecosystem Services Science-Policy Interface

Assessments must provide conditional predictions of the consequences of specific policy options, at well-defined spatial and temporal scales.

Charles Perrings,<sup>1\*</sup> Anantha Duraiappah,<sup>2</sup> Anne Larigauderie,<sup>3</sup> Harold Mooney<sup>4</sup>

www.sciencemag.org SCIENCE VOL 331 4 MARCH 2011



Intergovernmental Platform on Biodiversity & Ecosystem Services



+



= Great integrated Assessment capacity for global sustainability



**Earth System Sustainability Initiative:  
towards a new architecture  
building on existing strengths**

# Thematic Challenges.....

- A new generation of integrated Earth system models
- Predict risks of catastrophic regimes in the Earth system; in interlinked social-ecological systems
- Adaptability, transformability and innovation pathways
- Planetary stewardship and governance in the Anthropocene
- A global transition to sustainable food production within safe operating space
- A global energy transition that meets social needs and global sustainability criteria
- Economics in the Anthropocene (growth, wealth, equity, in a planetary saturation point)
- Global freshwater security

# FORECAST + CONFINE : Global freshwater security and moisture feedback over continents under climate change scenarios

W09525

VAN DER ENT ET AL.: ORIGIN AND FATE OF ATMOSPHERIC MOISTURE

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Continental precipitation recycling ratio  $\rho_c$

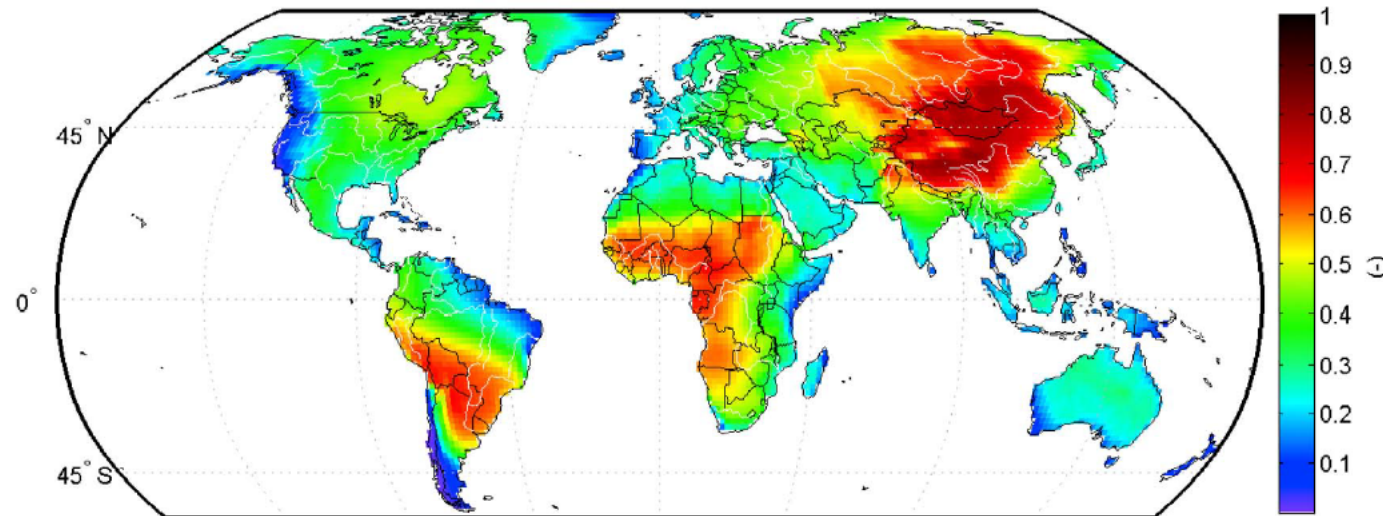


Figure 3. Average continental precipitation recycling ratio  $\rho_c$  (1999–2008).