Global Change

International Geosphere-Biosphere Programme
Issue 81 ▮ October 2013

REGIONAL TEMPERATURE RECONSTRUCTIONS

Landmark 2000-year analysis published

Broader view of the Anthropocene

Modelling civilisation collapse

Earth-System Science 2.0

PLUS: Visualisations of ocean acidification and PAGES 2k regional temperature reconstructions

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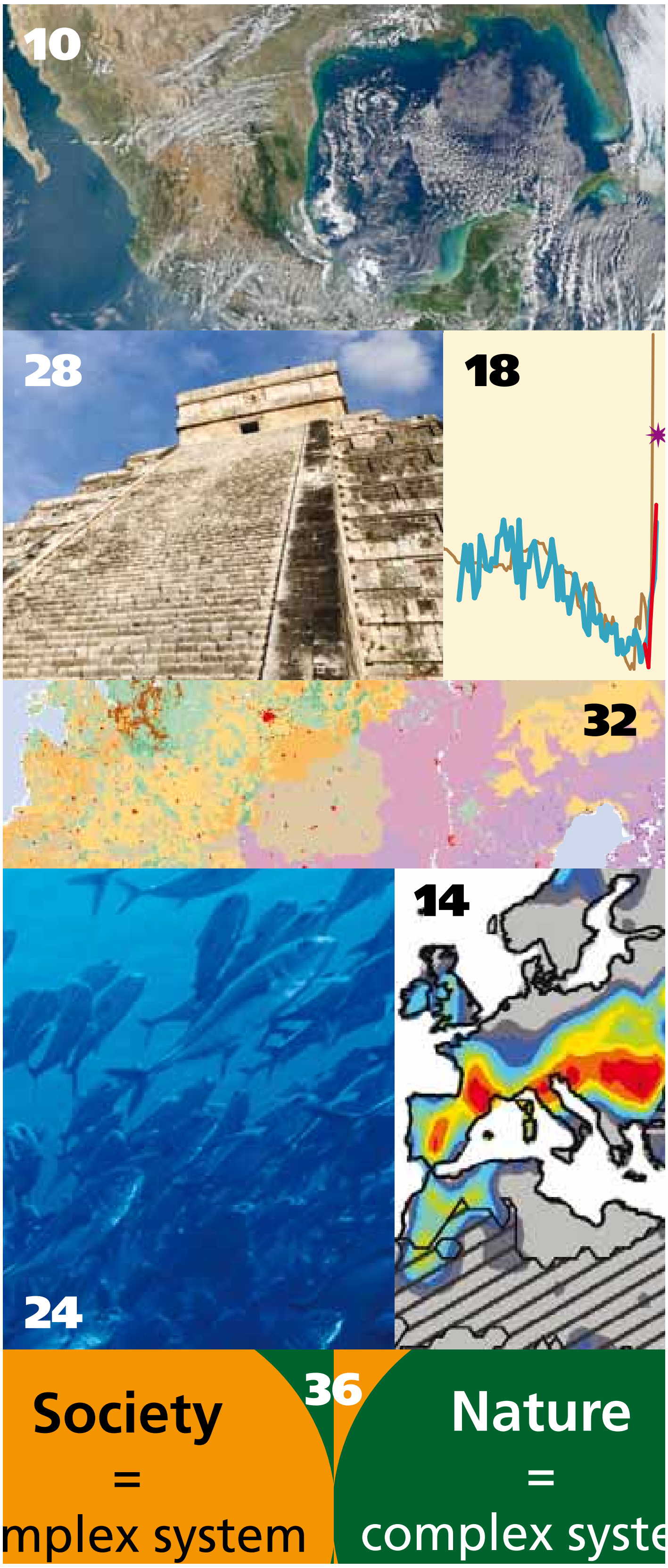
Earth-system science for a sustainable planet

Contents

Cover image

A scientist holds a slice of ice core in the cold room at the British Antarctic Survey, Cambridge (UK). Trapped air bubbles form an archive of past atmosphere and temperature. Photo credit: Pete Bucktrout.



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Sybil Seitzinger, Executive Director, IGBP

Nations set eight goals in 2000 to end poverty and hunger and to spur sustainable development. The target date for completion of these Millennium Development Goals (MDG) is 2015, but what will follow?

Arguably the most significant outcome of the UN's Rio+20 summit last year was an agreement to set universal Sustainable Development Goals (SDG) for all nations. While the process remains complex, it is on track for the SDGs to replace MDGs.

The MDGs were not legally binding. But they were clear and simple. By creating an agreed list of priority areas, the goals and underlying targets helped channel development aid.

With two years left to go, the MDGs have already scored notable achievements. In 1990, an estimated 12 million children under the age of 5 died each year. By 2011, this estimate was down to 7 million. Likewise, the goal to halve the number of people living on less than $1.25 (USD) a day has been met ahead of schedule. However, it is arguable this would have been achieved regardless because of China's rapid economic development.

Some areas, though, received less attention. Only one MDG explicitly tackled the environment, and environmental considerations were not embedded across the other goals.

Let's spin back to 2000 again. In the year nations created history by setting MDGs, Nobel Laureate Paul Crutzen created a stir at IGBP's scientific committee meeting in Cuernavaca (Mexico) by declaring that we'd exited the Holocene and entered the Anthropocene.

In a single word, the Anthropocene captures humanity as the prime driver of change within Earth's life support system. It captures a profound level of interconnectivity between societies through trade and communications that amplify our environmental impacts. And it captures a new collective responsibility for the changes we are making to the Earth system.

The Anthropocene has implications for SDGs: the interconnections between social, environmental and economic spheres must be considered for the formulation of the goals and their underlying targets and indicators, but how does science engage with this process and at what level?

Many avenues are available for experts to have input. For example, a recent IGBP-supported commentary in *Nature*, "Sustainable development goals for people and planet" has been presented to the UN working group set up to oversee the SDG process.

In the past year, I've attended workshops organised by the UN's Environment Programme (UNEP) to look at options for how the environment could be incorporated in SDGs (see news, p. 4). We concluded that where appropriate, goals and targets should be integrated to include social, environmental and economic dimensions and at the same time designed to avoid conflicts between goals and targets. Furthermore, targets must be scientifically credible and verifiable, and they must be formulated to break the links between socio-economic development and unsustainable resource use, for example, by promoting efficiency.

We must accept that these challenges are huge. The UNEP workshop I will attend in November is one step towards identifying environmental priorities that fulfill these criteria.

Ultimately, the SDGs could become one of the most significant international policy developments in recent years. If properly formulated, the goals have the potential to add up to genuine long-term sustainability. This is a goal worth aiming towards.

> “The goals have the potential to add up to genuine long-term sustainability.

Jonas Förare

IPCC: FIFTH REPORT

THE Intergovernmental Panel on Climate Change (IPCC) launched the first part of its latest report in Stockholm on 27 September. The report's summary for policymakers contained 19 headline statements relating to past, present and future climate and offered the clearest assessment yet on the changes likely this century.

Around 70 scientists from the IGBP community are contributing to the IPCC's Fifth Assessment Report. Global Carbon Project Chair Corinne Le Quéré took part in the tense discussions between scientists and national representatives, which ran night and day to finish on time. IGBP also joined the five-day meeting as an official observer of the process.

In a first for IPCC, a major public forum took place the day after negotiations ended to discuss the report. Organised by IGBP, the forum attracted an audience of 480 people to Stockholm's Kulturhuset, with 4744 viewers joining the livestream online. Thomas Stocker, IPCC Working Group I Co-chair, joined Markku Rummukainen and Deliang Chen, two IPCC authors from the universities of Lund and Gothenberg (Sweden), plus IGBP Executive Director Sybil Seitzinger. The event was co-sponsored by a range of Swedish organisations and funded by the UN Foundation and Swedish funding agency Formas.

UNEP report on Sustainable Development Goals

A NEW report recommends that the proposed UN Sustainable Development Goals (SDGs) better integrate environmental goals and targets than the Millennium Development Goals. The discussion paper, "Embedding the environment in Sustainable Development Goals", was published by the United Nations Environment Programme (UNEP) in August.

UNEP's Chief Scientist Joseph Alcamo hopes the document will feed into the international talks on SDGs. The process is a result of several roundtable meetings organised by UNEP and involved many experts, including IGBP's Executive Director Sybil Seitzinger.

Led by Alcamo, the authors proposed six criteria for embedding environmental sustainability in SDGs, including focusing on environmental issues with strong links to socio-economic developmental issues and giving priority to critical "irreversible" environmental changes. The report advises policymakers to build goals and targets that are scientifically credible and verifiable and concludes all goals need specific and measurable targets and indicators.

While the report covers data and reporting issues, it stops short of identifying environmental priorities. More meetings are planned in the coming months to hammer out these main concerns. Contact Sybil Seitzinger for more information.

Writing from Bangkok

THE Asia-Pacific Network for Global Change Research funded a "Write a Paper" workshop as part of the IGBP synthesis led by Pauline Dube in Bangkok at the end of August. The aim of the workshop was to improve research-writing skills of academics from nations such as Bangladesh and Cambodia, to increase success rates for submissions to peer-reviewed journals.

Franz Dejon

DIVERSITAS transitions

ANNE-HELENE Prieur-Richard will serve as the Acting Executive Director of DIVERSITAS during the programme's transition to Future Earth. The former Deputy Director stepped in for Anne Larigauderie, who is now Head of Science in Society at the International Council for Science (ICSU). See diversitas-international.org.

futurearth

Director appointed

Frans Berkhout, a professor of Environment, Society and Climate in the Department of Geography, King's College London, became Interim Director of Future Earth last July. Former Director of the Amsterdam Global Change Institute, Berkhout will serve at the new programme's temporary Paris offices through the transition period, until the permanent Secretariat is up and running in 2015. He is a lead author on the Intergovernmental Panel on Climate Change Fifth Assessment Report.

Scientific committee named

Former IGBP Vice-chair Mark Stafford Smith has been appointed Chair of Future Earth. His Vice-chairs will be Belinda Reyers from South Africa and Melissa Leach from the UK. Many past and present members of IGBP committees are also represented, including Cheikh Mbow, Eduardo Brondizio, Sandra Diaz, Corinne Le Quéré and Dahe Qin. Future Earth's first scientific committee meeting is in South Africa, 19-21 November.

Secretariat bids

The alliance of partners developing Future Earth received 22 expressions of interest from countries keen to host the secretariat or a regional node.

Blog launched

In July, Future Earth launched a blog with articles and opinions focused on global sustainability. The blog features video interviews with, for example, Richard Wilkinson, the author of best-seller *The Spirit Level*, and Melissa Leach, Future Earth's Vice-chair. See futureearth.info.

Website for IHOPE

THE Integrated History and future of People on Earth (IHOPE) initiative launched a new website this summer, http://ihopenet.org/. The fruits of the project can be viewed there, as well as in the pages of this issue (see features: AIMES 2.0, p. 10; PAGES 2k, p. 18; and Maya modelling, p. 28).

© iStockphoto.com/Konrad Mostert

Australian rains halted sea-level rise

THE world's sea level has been rising by about 3 mm every year for several decades – but not during an 18-month period across 2010 and 2011. Global sea level reversed, falling 7 mm.

A team of researchers led by John Fasullo of the US National Center for Atmospheric Research in Boulder, Colorado, figured out why (*Geophysical Research Letters*, doi:10.1002/grl.50834). A combination of two climate patterns, La Niña and the Southern Annual Mode, led to record-breaking heavy rains and flooding in Australia.

The amount of water that sank into the soils of the Australian Outback or evaporated back into the air was enough to make a difference in global sea level. Since 2011, sea level is back on the rise and is accelerating.

ANTHROPOCENE GOES MAINSTREAM

WRITERS of some recent apocalyptic thrillers and Hollywood movies have been turning to Earth-system science for inspiration. Perhaps it's time to coin a new term for an emerging breed of fiction – "Anthro-fi" – that tackles the wider implications of living in the Anthropocene.

Last May saw the release of the summer blockbuster *After Earth* starring Will Smith. The film follows a father and son returning to Earth a millennium after humanity somehow abandoned it following widespread ecological collapse caused by humans.

After Earth's producers took a novel approach to outreach. They commissioned scientist and educator Joseph Levine to create a website to accompany the film. The site explores the science behind global change and large-scale ecological challenges facing humanity. Visitors can learn about the Anthropocene and the Earth system. They also get an introduction to planetary boundaries and planetary stewardship, concepts meant to help avoid the film's unlikely premise altogether.

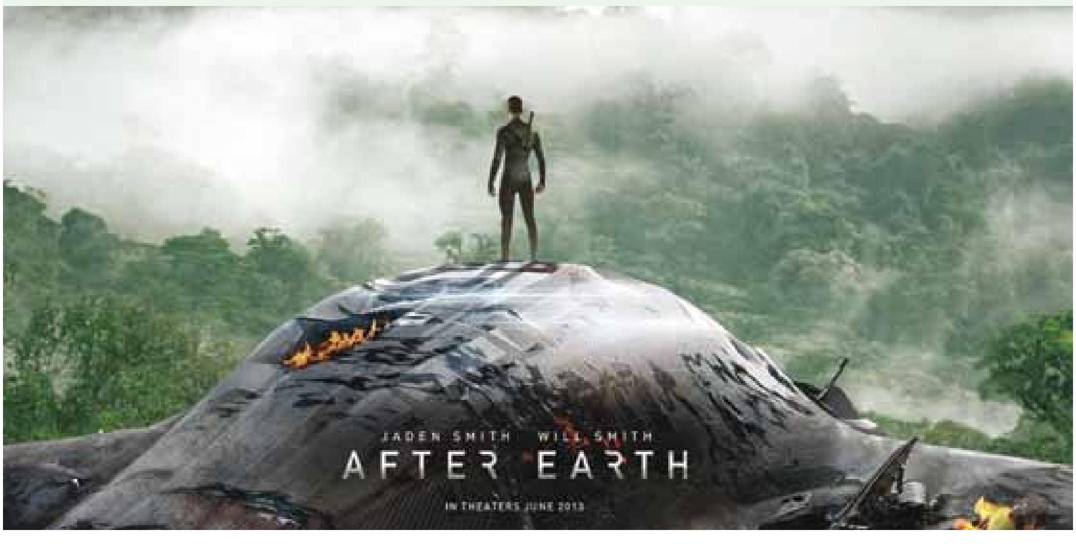
IGBP worked with Levine to develop content, which also features input from NASA and the National Oceanic and Atmospheric Administration (NOAA). The website includes a short data visualisation co-produced by IGBP on the Anthropocene, as well as the recent commentary in the journal *Nature* on "Sustainable development goals for people and planet", co-authored by several IGBP community members, including Priya Shyamsundar of the scientific committee.

Also in May, Dan Brown, author of the bestseller *The Da Vinci Code*, published his latest novel, *Inferno*. Brown included IGBP's graphs of the "Great Acceleration" published in the first IGBP synthesis (Steffen *et al.* 2004). The concept of the Great Acceleration – 24 graphs showing exponential growth in socio-economic and Earth-system indicators – is central to the plot of this fast-paced thriller about an unhinged geneticist bent on solving the global population "problem" alone.

Inferno and *After Earth* have been associated with a genre of fiction known as "cli-fi" for "climate fiction". The term is used to pigeonhole books and films such as *The Day After Tomorrow* (2004) and Ian McEwan's novel *Solar* (2010) that tackle climate and related issues.

But these more recent examples are broader than climate. In their own unique ways, both *After Earth* and *Inferno* explore how decisions or actions made now may have immediate global repercussions that are irreversible on millennial timescales.

It seems there's a cultural awakening around the idea of the Anthropocene. Several well-known journalists have announced they are writing Anthropocene-themed books, including David Biello of *Scientific American* and British freelancer Gaia Vince. In September, Margaret Atwood published *MaddAddam*, the third part of her "dystopian" and "speculative fiction" trilogy (which started with *Oryx and Crake* in 2003). The novel finishes a tale of vigilante population "interventions" by a scientist and his team, to fix what he sees as the world's socio-economic problems.



Sony Pictures

Q&A WITH FUTURE EARTH'S SCIENCE COMMITTEE CHAIR

Photo: courtesy of ICSU

Mark Stafford Smith is the Science Director of CSIRO's Climate Adaptation Flagship based in Canberra, Australia, and former Vice-chair of IGBP. He recently spoke with Johannes Mengel, Web Editor for the International Council for Science (ICSU). A condensed version of their conversation follows (read the full Q&A at Future Earth's blog, futureearth.info).

Q: Tell us a little about yourself. What is your background and research?

Mark Stafford Smith [MSS]: I started out as a systems ecologist with a focus on drylands, and spent a long time based in Alice Springs in Australia, first working on arid zone ecology and then looking at people's decision-making, interactions between pastoral production and conservation, and finally trying to understand how regional economies work in remote areas. At the same time, I was involved with IGBP, initially as part of its old Global Change and Terrestrial Ecosystems Project, but later as a member of the IGBP Scientific Committee.

Q: You were Co-chair of the Planet Under Pressure conference in March 2012, along with UNESCO's Lidia Brito. What did the conference achieve?

MSS: What was amazing about the conference was seeing such diversity of skills and perspectives coming together in the one place, trying out all sorts of novel ways of interacting. Assembling the research community for conferences like this should be one of the regular but not too frequent things that Future Earth does.

Q: What is your vision for Future Earth?

MSS: Future Earth has an expansive potential agenda, but we also need to focus. One way of thinking about this would be to use the three research themes as a lens for understanding our stakeholder needs.

I see the main role of the first theme as really continuing the important existing work of the projects, albeit perhaps with new focus. The second and third research themes open up new opportunities that some of the projects have started pushing into, such as global development, which could in part support sustainable development goals, and the transition into a different type of economy.

Q: How far beyond the current global environmental change programmes will Future Earth go?

MSS: Future Earth has to maintain continuity with the existing global change work while opening the door to new opportunities. In doing so, Future Earth should seek expertise from new communities such as economics, engineering, history and the arts.

Another top priority is stronger engagement with decision makers who use our work. That's not to say that there shouldn't be some basic research. But a lot more of our research needs to be clearly user-inspired and solutions-oriented. Somewhere in Future Earth we need that true, fundamental engagement which helps tell us what knowledge is really going to be useful in the next five to ten years.

Q: What are the priorities in the first year?

MSS: The immediate priority for Future Earth is to ensure that there is continuity for the existing projects. We need to design the modus operandi by which the projects move into Future Earth, while keeping our options open in terms of new activities and new communities. All the while, we have to live and breathe the intention to engage with decision-makers. We have to ensure that that engagement is there from the start.

EVENTS

2013

November

5-8. IGBP Officers meeting. Gaborone and Maun, Botswana

11-22. IPCC COP19. Warsaw, Poland

18-22. 6th International Nitrogen Conference. Kampala, Uganda

19-21. Future Earth Science Committee. Gauteng, South Africa

December

1-4. IGFA/Belmont Forum meeting. Cape Town, South Africa

9-13. American Geophysical Union Fall Meeting. San Francisco, USA

2014

January

20-21. Future Earth projects meeting. Washington DC, USA

March

19-21. Global Land Project: 2014 Open Science Meeting. Berlin, Germany

April

7-11. IGBP Scientific Committee meeting. Bangalore, India

7-12. Arctic Science Summit Week. Helsinki, Finland

May

12-16. 4th iLEAPS Science Conference. Nanjing, China

12-16. Adaptation Futures 2014. Fortaleza, Brazil

June

23-27. IMBER Open Science Conference. Bergen, Norway

September

22-26. 13th IGAC Open Science Conference. Natal, Brazil

IGBP Scientific Committee Meeting

THE IGBP's 28th Scientific Committee meeting was held in Bern, Switzerland, 16–19 April. The three-day meeting tackled IGBP's twin priorities: the transition to the new Future Earth initiative and the development of IGBP's second synthesis.

The main outcome from the meeting was the decision to complete the transition of IGBP's projects to Future Earth by December 2015, as IGBP comes to a close at this time. James Syvitski, IGBP Chair, proposed an event in 2015 to mark almost three decades of the programme.

The meeting also discussed IGBP's second and final synthesis which will be conducted in three parts: first, high-level papers will explore the integrated natural and social science perspective of the challenges of the Anthropocene, in collaboration with IHDP. Second will be an analysis of how the discipline of Earth-system science has developed in the context of its contribution to global sustainability. And, finally, a series of papers from IGBP's core-projects will synthesise project findings, to inform the projects' future visions as they transition into Future Earth.

The meeting was organised by the Past Global Changes project, and coincided with the annual Swiss Global Change Day, a one-day symposium highlighting the latest research in Earth-system science organised by ProClim, IGBP's Swiss national committee. James Syvitski and Sybil Seitzinger both spoke at the packed event.

IGBP Synthesis Committees*

Core projects

Paul Monks (Chair)
Cheikh Mbow
Ramesh Ramchandran
Megan Melamed
Giovana Mira de Espindola
Sybil Seitzinger

Anthropocene

Eduardo Brondizio (Co-chair)
James Syvitski (Co-chair)
John Dearing
Peter Verburg
Priya Shyamsundar
Patricia Matrai
Frank Biermann
Arthur Chen
Karen Seto
Amy Dahan-Dalmedico
Sybil Seitzinger
Ninad Bondre

Earth-system science

Jan Willem Erisman (Chair)
Martin Claussen
Jose Marengo
Guy Brasseur
Mitsuo Uemastu
Christiane Lancelot
Thorsten Kiefer
Philippe Ciais
Sybil Seitzinger

* Subject to change

LIMITS TO (PHYTOPLANKTON) GROWTH

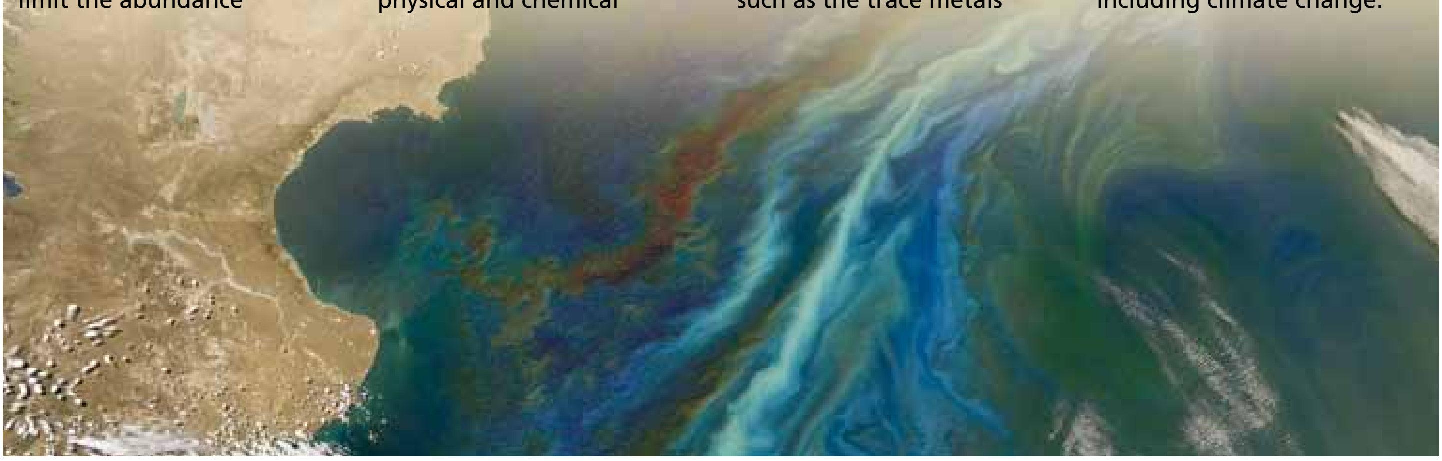
HUMANS are upsetting the balance of nutrients in the ocean, with agricultural runoff and other sources. For example, atmospheric deposition of "fixed" nitrogen to the open ocean has tripled since 1860, and will probably increase another 10–20% by 2050.

Understanding how these nutrient levels are changing and how this will affect biogeochemical cycles in the future is important. Nutrients such as nitrogen, iron and phosphorus limit the abundance of phytoplankton, the tiny single-celled ocean organisms that photosynthesise and play a crucial role in the carbon cycle.

Christopher Mark Moore of the University of Southampton (UK) and his colleagues recently published a comprehensive review in *Nature Geoscience* (*Insight – Marine cycles in flux,* doi:10.1038/ngeo1765) on "processes and patterns" of nutrient limitations in the ocean. They included physical and chemical processes in their assessment of biological patterns. The analysis stemmed from a workshop from IGBP's Fast Track Initiative on Upper Ocean Nutrient Limitation.

While nitrogen is the primary limiting nutrient in many places in the oceans, iron is limiting at high latitudes and upwelling areas, such as off the coast of South America in the Humboldt system. (In some places, nitrogen and phosphorus co-limit productivity.) Micronutrients, such as the trace metals zinc and cobalt or vitamin B_{12}, can have secondary effects in different regions of the oceans. For example, several tests showed cobalt being a secondary limiting nutrient after iron in the relatively nitrate- and phosphate-rich surface waters south of Alaska.

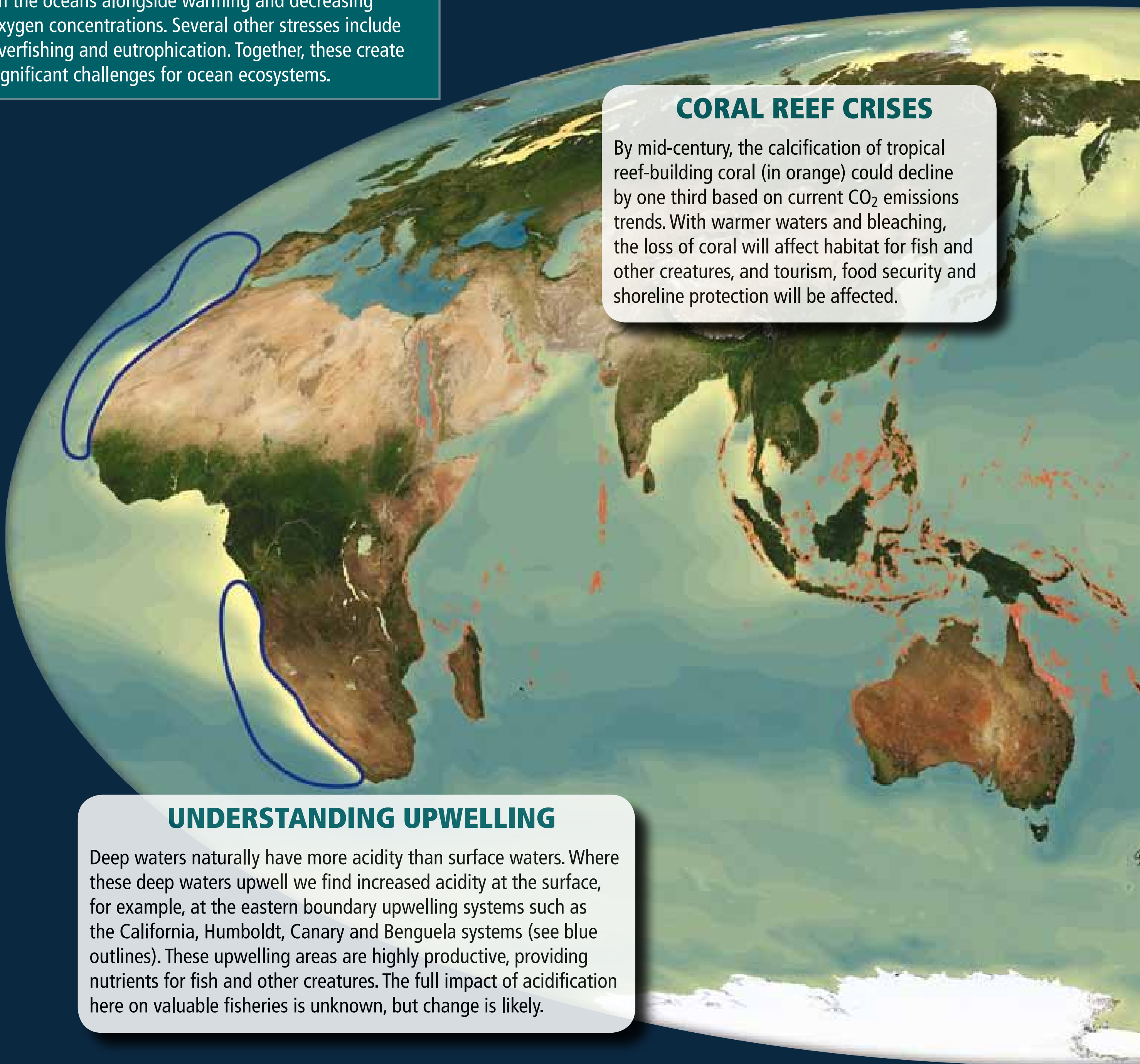
By pulling all of these complex interactions together, the authors have painted a useful overall picture based on decades of research, with a new view of future implications, including climate change.



NASA/Norman Kuring

"HOT, SOUR & BREATHLESS"

Ocean acidification is one of the big three stressors on the oceans alongside warming and decreasing oxygen concentrations. Several other stresses include overfishing and eutrophication. Together, these create significant challenges for ocean ecosystems.



CORAL REEF CRISES

By mid-century, the calcification of tropical reef-building coral (in orange) could decline by one third based on current CO_2 emissions trends. With warmer waters and bleaching, the loss of coral will affect habitat for fish and other creatures, and tourism, food security and shoreline protection will be affected.

UNDERSTANDING UPWELLING

Deep waters naturally have more acidity than surface waters. Where these deep waters upwell we find increased acidity at the surface, for example, at the eastern boundary upwelling systems such as the California, Humboldt, Canary and Benguela systems (see blue outlines). These upwelling areas are highly productive, providing nutrients for fish and other creatures. The full impact of acidification here on valuable fisheries is unknown, but change is likely.

FACTS

- Without a doubt, the pH of the world's ocean is falling as a result of human CO_2 emissions to the atmosphere. To date, acidity has increased by 30%.
- Ocean acidification is caused by carbon dioxide gas (CO_2). The ocean absorbs about a quarter of the CO_2 added to the atmosphere from human activities each year. Ocean storage of CO_2 greatly reduces the impact of this greenhouse gas on climate.
- When CO_2 gas dissolves in seawater, carbonic acid is formed, changing the chemical composition of the ocean: ocean acidification. The current rate of change is unprecedented in the past 300 million years.
- As the ocean becomes warmer and its acidity increases, its capacity to absorb CO_2 from the atmosphere decreases.
- We do not fully understand the biogeochemical feedbacks to the climate system that may arise from ocean acidification.
- The impact of these changes on marine ecosystems is also not fully understood. However, earlier in Earth's history, a rapid shift in ocean acidification has been linked to mass extinction of species in the oceans.

POLAR PROBLEMS

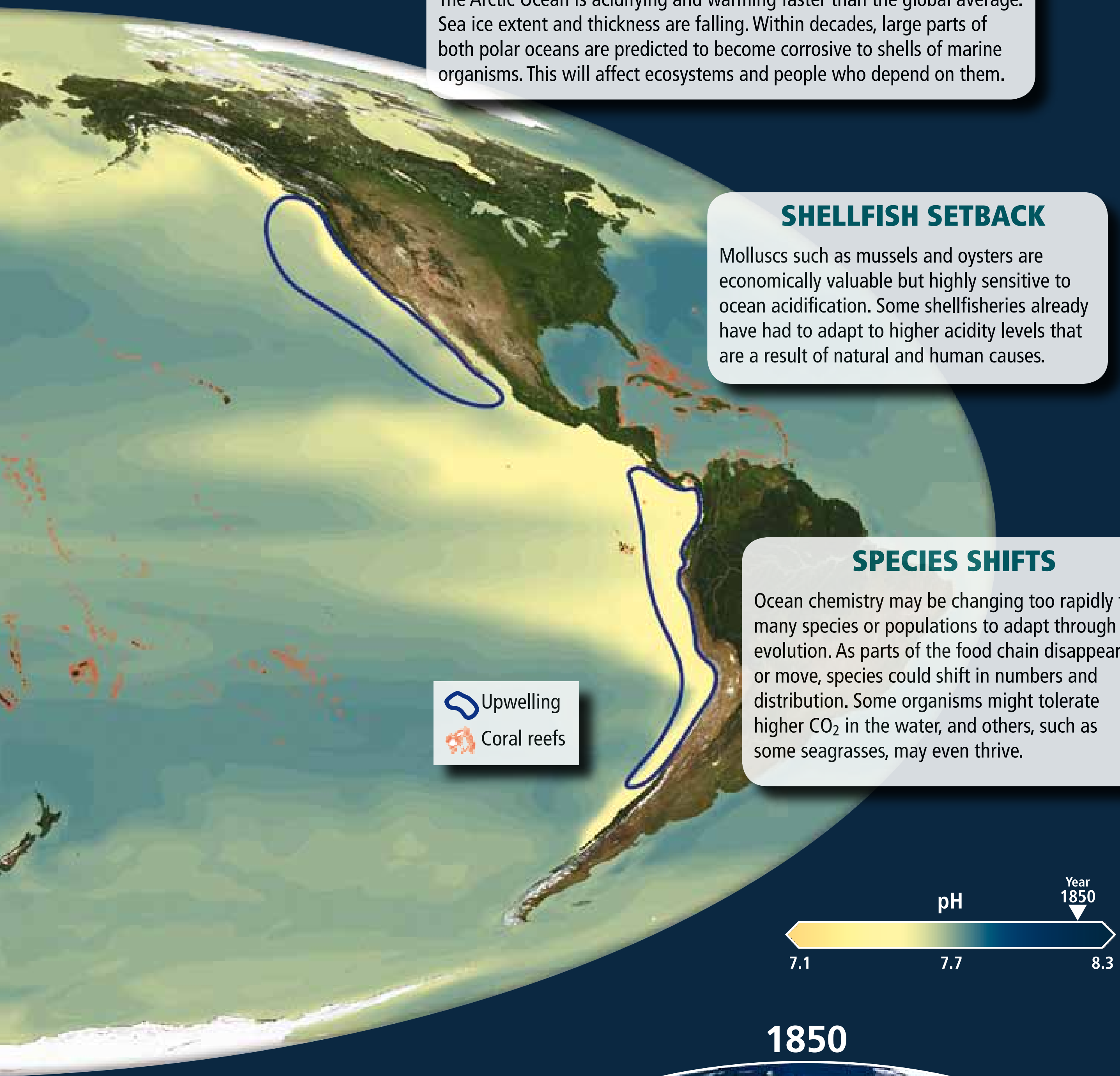
The Arctic Ocean is acidifying and warming faster than the global average. Sea ice extent and thickness are falling. Within decades, large parts of both polar oceans are predicted to become corrosive to shells of marine organisms. This will affect ecosystems and people who depend on them.

SHELLFISH SETBACK

Molluscs such as mussels and oysters are economically valuable but highly sensitive to ocean acidification. Some shellfisheries already have had to adapt to higher acidity levels that are a result of natural and human causes.

SPECIES SHIFTS

Ocean chemistry may be changing too rapidly for many species or populations to adapt through evolution. As parts of the food chain disappear or move, species could shift in numbers and distribution. Some organisms might tolerate higher CO_2 in the water, and others, such as some seagrasses, may even thrive.



1850

ACIDIFYING WATERS

In 1850, average ocean pH was about 8.2 (small map). According to models based on business-as-usual scenarios, with no action taken to decrease carbon emissions, average ocean pH will drop to about 7.8 by 2100 (large map).

This map and other information will be reported in an upcoming summary for policymakers from IGBP and its partners.

MAPS: Félix Pharand-Deschênes, Globaia; pH DATA: Tatiana Ilyina, Max Planck Institute for Meteorology; INFORMATION: IGBP/SCOR/IOC Summary for policymakers on ocean acidification (2013)

AIMES 2.0: TOWARDS A GLOBAL EARTH SYSTEM SCIENCE

Geologists, biologists and other scientists are no strangers to the interlinked nature of Earth's complex adaptive systems. Now, Earth-system researchers need to consider adding social systems to their complex webs of research. **Sander van der Leeuw** examines how one IGBP programme is working to do so.

Earth is a complex place: the planet is composed of oceans, deserts, forests, animals, microbes, volcanoes and more, and everything interacts to create a whole. Now, add human structures to that list: governments, the Internet, social movements, individual desires. Those, too, are complex, interacting systems. And these two worlds – the natural and the human-made – are meshed together in a cyborg whole.

Over the last century or so, humans have increased their impact on the natural environment so much that they cannot be left out of the picture. No wonder, then, that the next step for Earth-system science, and for the many interdisciplinary researchers who work in that field, is to incorporate economics, governance and other human and social dimensions into their work.

A major section of the IGBP known as AIMES (Analysis, Integration and Modeling of the Earth System) will pursue this goal, by expanding beyond the natural and life sciences that composed Earth-system science until now.

Recently, AIMES sparked a dialogue between climate modellers and socioeconomic researchers.

Field work

For more than a decade, AIMES 1.0 has developed the field of Earth-system science. From this perspective, the planet is a coupled system of interacting physical, chemical and biological components; together, these components produce planetary-wide effects that are beyond their own individual dynamic forces. Changes wrought by the ocean's circulation patterns, for example, such as the El Niño–Southern Oscillation in the Pacific, have repercussions for weather patterns half a world away, in this case changing rainfall patterns in Europe. And the rapid accumulation of greenhouse gases in the atmosphere, due to human energy consumption, causes the Earth's polar icecaps to melt and sea levels to rise.

This perspective slowly became mainstream in global environmental change research, partly due to the success of AIMES; its forerunner, the Global Analysis, Integration and Modeling (GAIM) project; and its partner projects, for example, the World Climate Research Programme (WCRP) and the World Global Climate Model (WGCM). The GAIM project initiated serious efforts to model the carbon cycle involving a number of international teams. AIMES 1.0 has been instrumental in extending this approach to include the physical components of the climate system, from soils to water cycles to the atmosphere, as well as couplings to the biological components of the land and ocean carbon cycle, such as fisheries and coral reefs (Friedlingstein *et al.* 2006). As a result, the next Intergovernmental Panel on Climate Change (IPCC) report will include such coupled models.

More recently, AIMES sparked a dialogue between climate modellers and socioeconomic researchers to ensure greater consistency in IPCC's assessment process (Hibbard *et al.* 2007). This discussion highlighted the dual nature of the pressing challenges we face: climate change, financial crises, food security, pandemics, and energy availability and sustainability are symptoms of our geographic interconnectedness at a global scale on the one hand, while on the other hand, these challenges are topically interconnected as well – energy needs are connected to food and water security, and both are affected by climate shifts and

NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring financial markets, for example, as well as by government policies.

The dialogue also highlighted the pervasiveness of information and communication technologies in all human and societal endeavours (Helbing 2013). Because of our interconnectedness – through the Internet and our decision-making structures – nations and cultures increasingly must share the burden of these challenges. However, interconnectedness also provides a new universe of tools for research and engagement.

Taking on risk

These interconnections – both our planet's connected systems and our own societal links – are gaining more attention. But another aspect of how we understand global systems has received less attention: the changing nature of risks.

Ever since the Neolithic era began about 10,000 years ago, the nature of risks has slowly shifted from the environment to society. Over the past two centuries in particular, human activities have irrevocably changed planet Earth; our impacts are now so widespread that we dominate many aspects of the Earth system's dynamics. Hence, our major risks are no longer natural ones that are predominantly external to society, but social risks that are considered internal to society. In the process, societal dynamics and interventions in the environment have driven the Earth system to some of the limits of its safe operating space.

With global interconnections, as Helbing (2013) argues, more links between different parts of the Earth system and human societies substantially increase the probability of "risk cascades": local events that are in themselves seemingly minor can now lead to major global crises. The current global financial crisis amply demonstrates this kind of risk cascade, and the increased probability of such chain reactions also applies to potential pandemics, sea-level rise due to greenhouse gas emissions, and other challenges.

We have a hard time assessing the full effects of our actions.

These trends – more interconnections that lead to risk cascades – show the need for a new focus on future outcomes, in scientific research as well as for policy and society. The nature of human risk perception also adds to the urgency of this shift. Human interventions tend to be based on a very limited knowledge of the many complex processes involved in a challenge. Thus, we often are unaware of many risks that may be the consequences of our interventions.

Moreover, whereas humans generally mount interventions in response to relatively frequently observed phenomena, such interventions also have long-term effects on a system. Over time, therefore, risk patterns shift: frequently perceived short-term risks get fixed, only to give rise to unknown longer-term risks. In our daily lives, we as individuals focus on short-term risks and tend to ignore long-term ones (such as climate change), and our governments do the same. Because of this "risk bias", we have a hard time assessing the full effects of our actions, let alone their many-faceted impacts on the very complex real world (van der Leeuw 2010).

Because of the gulf between the perceived dimensions of a problem and any unperceived effects, the domain of unintended consequences always grows faster than our knowledge. While we think we know more about a system, we actually understand less because the system has disproportionately changed due to our actions. In the evolution of all social-environmental dynamics, there thus comes a point where a society is overwhelmed by the unintended and unanticipated consequences of its own actions – a "tipping point" that puts a society into crisis.

Arguably, this shift in risk spectrum is at the root of the various crises we are experiencing today. Our empirical, reductionist approach to science seems to have blinded us to unanticipated consequences: current scientific methods reduce the complexities of the Earth system to the point that a "clear" (but necessarily incomplete) explanation of phenomena emerges.

The trial-and-error methods of problem-solving that evolved from our current approach to science are inadequate to deal with issues facing today's rapidly changing global system. Over the past half-century, the recognition that many phenomena are complex (adaptive) systems has convinced us as Earth-system scientists that we need to adapt our thinking and approach. We require unprecedented amounts of information to drive new analytical and computational approaches and new tools to understand the multi-dimensionality of such complex systems across many scales in time and space. We need to ask fundamentally different questions, transforming both the conceptual/theoretical and epistemological foundations of the natural and social sciences.

Making a change

This shift moves the emphasis away from learning **from** the past towards learning **for** the future. Instead of studying "origins", "explanation" and "causality", research should move towards studying "emergence" and "anticipation". Rather than reducing the number of dimensions, research must enhance the complexity of our understanding through modelling and the design of multiple potential futures (van der Leeuw *et al.* 2011). These shifts will allow us to improve our ways of dealing with unanticipated consequences and to become

pro-active rather than **re**-active.

In response to this challenge, AIMES 2.0 economists and social scientists are arguing for a Global Earth System Science that aims to holistically study systems like the Internet, urban centers and how they are networked, the financial system, human health and more, all at a global scale (Finnigan 2003, Helbing 2013, Jaeger *et al.* 2013). This Global Earth System Science should extend the "Complex Adaptive Systems" perspective beyond the natural world to the social domain. Socio-environmental processes should be studied as an integral part of this new way of thinking, in order to develop evidence, concepts, and questions concerning the Global Earth System to help practitioners to reflect on their experiences and to assess possible consequences of their actions.

Such research should be designed to be truly global in three different senses: **physically**, looking at the Earth system in its entirety; **intellectually**, fusing all relevant approaches and disciplinary contributions to consider the topic holistically; and **demographically**, considering and ultimately engaging the whole human population. To achieve these goals, Global Earth System Science should combine advanced modeling and forecasting technologies with conversations that bridge the gap between science and society. AIMES 2.0 will embrace such a Global Earth System Science approach.

A central goal of Future Earth, the next embodiment of IGBP's work (see news story on p. 6), is to develop intensive, continuous, iterative exchange with societal stakeholders and decision-makers to stimulate public policy and societal responses. AIMES 2.0 will embrace that goal and will also promote an intellectual fusion between disciplines, to develop the insights that practitioners need.

The project will focus on questions that are core to the Future Earth initiative. These questions include determining the states and trends of key environmental processes and components, such as biodiversity, soils and more. Human-driven change and the social foundations of sustainable development need to be clarified, such as population growth, consumption habits and available technology. How do these fit into human wellbeing, equality, health, education and security?

To address these core concerns, AIMES 2.0 will consider the approaches, theories and models that will allow us to explain and, where possible, to anticipate the functioning of the Earth's socio-ecological systems. How do we understand the interactions between them, make projections for the future, and anticipate critical thresholds? These questions require determining the risks of crossing regional to global thresholds and planetary boundaries, which might induce tipping points and social-environmental crises due to global environmental change.

With these new tools and a new way of thinking, we hope to identify the patterns, trade-offs and options for equitable and sustainable use of resources and land. We need to ensure sustainable access to food, water, clean air, energy and materials for current and future populations. With that in mind, we have to consider the implications of climate change – for food, water, health, human settlements and ecosystems. The main question now will be how humans might adapt to climate change and find ways to harness the ecosystems services we have, in order to soften impacts of climate shifts in the future.

We need to find the links between biodiversity, ecosystems, human wellbeing and sustainable development. We expect that this approach will simultaneously rejuvenate the science, energise the scientific community, enlarge it by more directly involving new disciplinary communities, and contribute in a major way to solving some of the challenges that our global society faces in the 21st century. ■

Global Risk Networks

Data-driven approaches have allowed Earth-system scientists to illustrate the strong connections in global networks, as Dirk Helbing of the Swiss Federal Institute of Technology in Zurich wrote in a recent perspective in *Nature*. Models inspired by the human nervous system, for example, or nuclear chain reactions that might lead to a "human time bomb", where one imploding node sets off explosions down interconnected pathways, show both the good and the bad of our tightly linked networks. Models can include economic inequality, wars, biodiversity, organised crime, air pollution and even the slowing growth of the Chinese economy.

Global Earth System Science should combine modelling and forecasting with conversations between science and society.

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HOW SOILS SEND MESSAGES ON HEAT WAVES

Extreme heat waves cost lives and money. We're destined to see more in the future, so better predictions of where they're going to strike next are important. **Brigitte Mueller** and **Sonia I Seneviratne** highlight a strong link between soil moisture and heat waves that could pave the way for more accurate forecasts.

A decade ago, Europe endured brutally hot temperatures. More than 20,000 people died prematurely, including many elderly people living in major cities. Rivers ran low, forest fires dotted the landscape, glaciers melted and crops withered as the region set records for highest temperatures in up to 500 years in some places.

Another heat wave in 2010 bathed the Northern Hemisphere in more record-breaking heat, most strongly affecting Russia, where temperatures were 10°C or more higher than usual in July. And in 2011, a drought began in Texas that drew international attention, as farmers lost cattle and a heat wave led to fires and more agricultural losses.

These high-impact hot weather events underscore the importance of understanding the evolution of heat waves and predicting the occurrence of hot temperature extremes. Predictions will help people to reduce the impacts of these events. And the tools to do it lie beneath our feet: soils, and the moisture they hold, are apt indicators of hot times to come.

A lack of soil moisture can trigger a spike in air temperatures – and a heat wave.

Climate modelling with soil

With new analyses, we show that soil moisture can be a powerful indicator of approaching extreme weather cycles, similar to the longer-term forecasting role played by sea-surface temperatures. Researchers have long used anomalies in sea-surface temperature patterns, El Niño–Southern Oscillation or the North Atlantic Oscillation, to make seasonal predictions. The underlying reason is the high heat capacity of water, which makes the ocean an effective sink for storing heat.

On land, the analogue to sea-surface temperature is soil moisture. Water can be stored in soil like a sponge, in the pore spaces in between soil particles or coated on them. That means that soil acts as storage for both energy (in the form of heat) and water. In addition, the water content also affects the heat exchanges at the land surface.

If the amount of water stored in soils is high, then an increase in temperature and sunlight (or radiation) leads to some important changes. As the heat causes the soil moisture to evaporate, this process requires a substantial amount of energy, which cools the temperatures of both soil and air, a process known as evaporative cooling. This mechanism buffers increases in temperature in the soil and the air above it.

If atmospheric conditions favour heat-wave development, whether that heat wave grows or collapses often depends on soil moisture. Sufficient moisture could trigger enough evaporative cooling to hamper or at least dampen the severity of an oncoming heat wave.

On the other hand, on the heels of a long hot spell, soils may have already released any moisture they contained. Dried-out soils have lost their ability to buffer temperature increases, which means that a lack of soil moisture can trigger a spike in air temperatures – and a heat wave.

Indeed, our study published last year in the journal *Proceedings of the National Academy of Sciences* (10.1073/pnas.1204330109) shows that in several regions of the planet, the evolution of heat waves requires a lack of soil moisture.

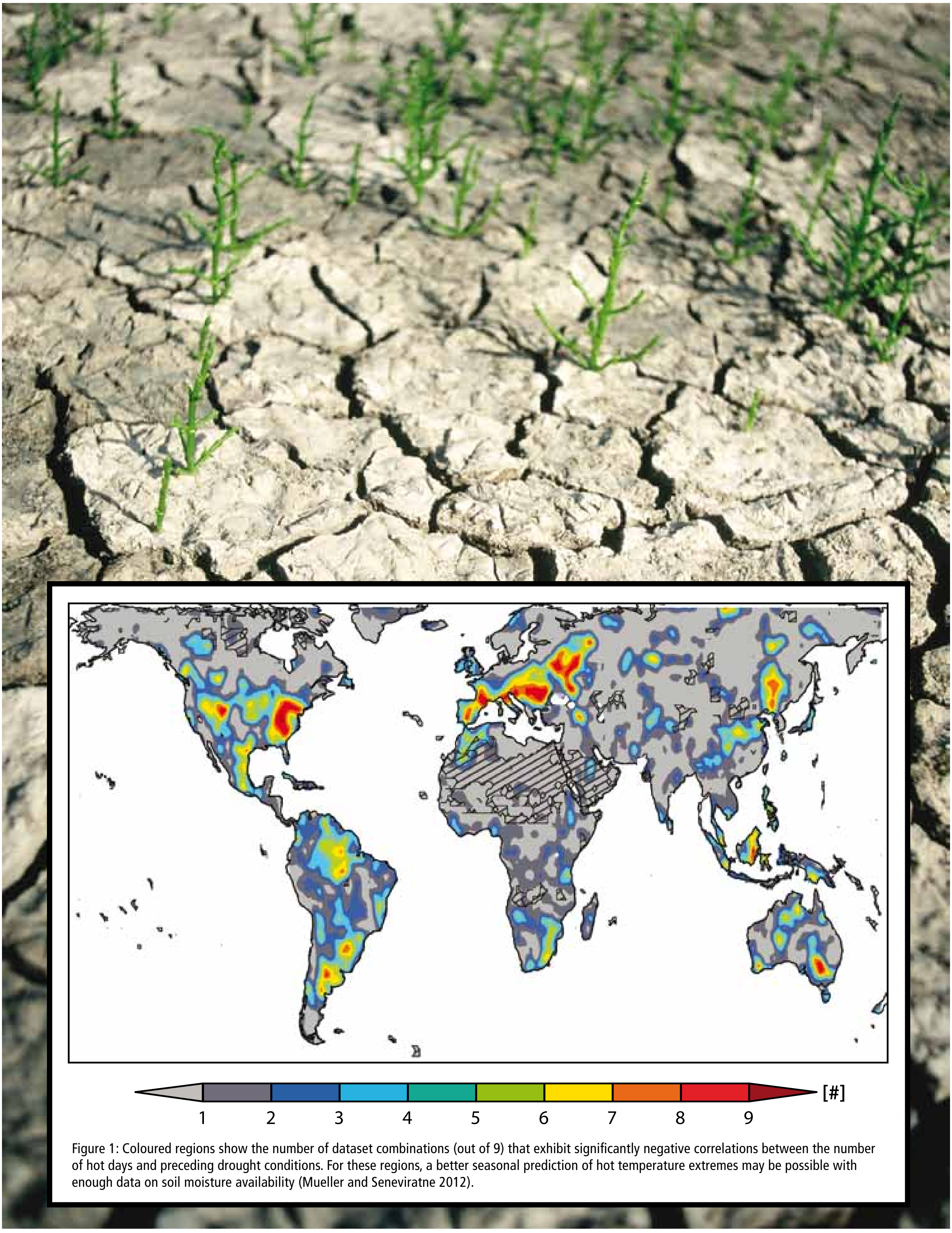

Figure 1: Coloured regions show the number of dataset combinations (out of 9) that exhibit significantly negative correlations between the number of hot days and preceding drought conditions. For these regions, a better seasonal prediction of hot temperature extremes may be possible with enough data on soil moisture availability (Mueller and Seneviratne 2012).

Neither too wet nor too dry

In the last decade, studies of the relationships between soil moisture and temperatures have made some headway (e.g. Koster *et al.* 2006, Seneviratne *et al.* 2010, Hirschi *et al.* 2011). In particular, researchers have shown that soil moisture has a strong influence on air temperatures in regions that can be considered "transitional" between wet and dry climate zones. These transitional regions are "just right" – a change in soil moisture here makes a difference, versus in regions that are either really wet or really dry.

In the case of wet climate regions, soils always have enough moisture, the rate of evaporation does not depend on it, and foreseeing the development of heat waves with the aid of soil moisture is impossible. In dry areas, moisture levels in soils are always very low and do not contribute much towards evaporative cooling. But in transitional regions, where the moisture levels are neither too high nor too low, we expect soil moisture and evaporation to influence temperature.

With enough data, scientists could improve the prediction of very hot days or heat waves.

While models and regional studies agree overall on the feedbacks of soil moisture on temperature, global-scale observations of the real world are lacking. A main limitation for these investigations is that researchers are missing a baseline for soil moisture around the world, measured with satellite instruments or field observations (see e.g. Seneviratne *et al.* 2010 for an overview). But there are plenty of rain, snow and other precipitation observations, which can be used to build records of drought and water scarcity. These data underlie the standardized precipitation index (SPI), developed two decades ago for drought planners, that we used as the missing baseline – and as our proxies for soil moisture.

A previous study examining heat waves in southeastern Europe (Hirschi *et al.* 2011) demonstrated a strong link between moisture deficits (or droughts) estimated from the SPI and rising temperatures that developed into extremely hot temperature days. In our study, we expanded that analysis to the global scale. Because spikes in temperature are deadlier and costlier during hot summer months, we first determined the hottest month of each year in grid cells plotted across the globe. We then took counts of the number of days with hot temperature extremes in that hottest month, and related that information to the SPI drought indicator over the three months preceding the hottest one.

Analysing results from several temperature and precipitation datasets, we could see a strong correlation in many areas between low soil moisture levels and the very high temperatures that followed. This relationship between soil moisture and hot temperature extremes shows that a lack of soil moisture during a drought would lead to later temperature spikes.

Spain is a good example of such a relationship (a so-called negative correlation): the country's hottest month of the year is July. If April to June have been unusually dry, the number of hot days in July is usually higher than if those previous three months were wet. We looked at 32 years of data; of those, 22 years had dry conditions from April to June. In more than 70% of those years with dry springs, the number of hot days in July was above average.

That same relationship holds elsewhere: the likelihood of an above-average number of hot days in the hottest month of each year, following on the heels of dry periods, is 70% in most of South America, the Iberian Peninsula and eastern Australia. After wet conditions, the probability falls to 30–40%.

We can see this relationship between low soil moisture after drought and spiking temperatures in hot months, for example, in the eastern US, south and southeastern Europe, and New South Wales in Australia (see Figure 1). These regions where soil moisture affects temperature are much more widespread than previously assumed, based

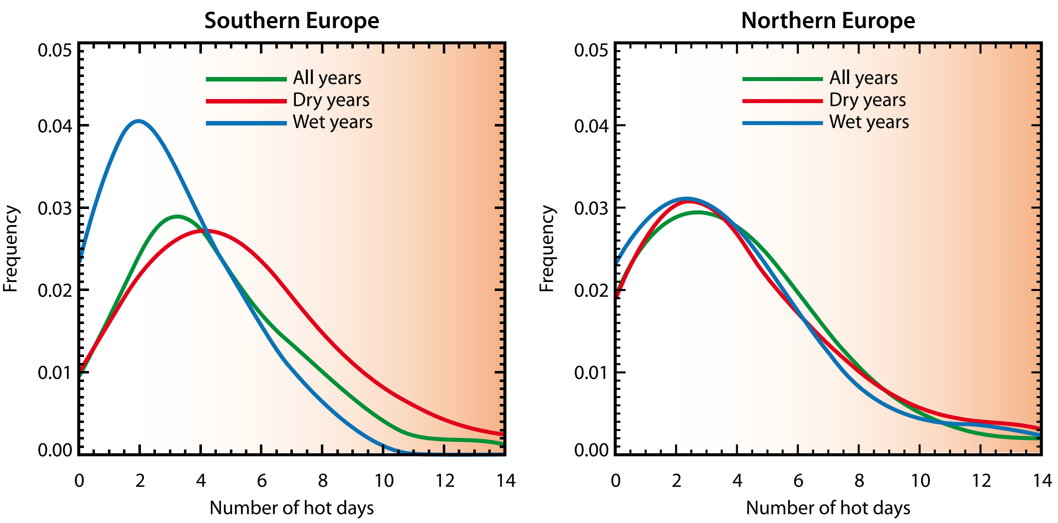

Figure 2: In southern Europe (left), during years with low soil moisture levels, the occurrence of hot temperature extremes (red probability curve) shifts towards more hot days compared to the distribution for all years (green curve). The slightly broader shape of the curve indicates an increase in the probability that the number of hot days will be very high. On the other hand, if soil moisture is high (blue curve), low numbers of hot days are more likely. In northern Europe (right), the differences between the occurrence after dry, normal and wet conditions is much smaller; soil moisture conditions do not influence the occurrence of high temperature extremes in that region.

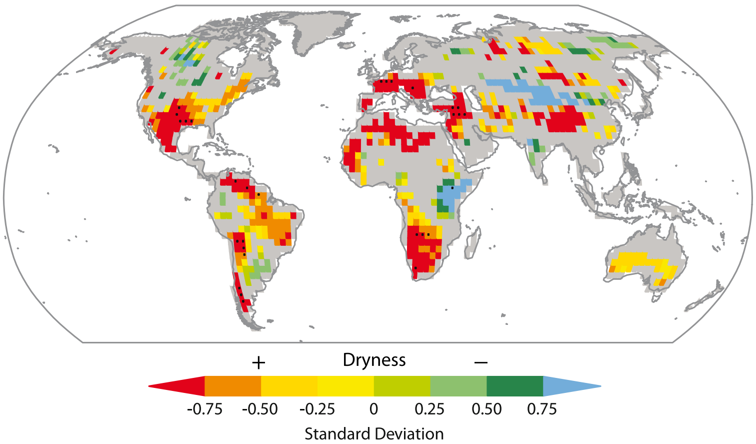

Figure 3: Model simulations of projected changes in soil moisture (or dryness) from 2081 to 2100 compared to values from 1980 to 1999, based on global climate simulations under the International Panel on Climate Change (IPCC) emission scenario SRES A2. Increased dryness is indicated with yellow to red colours, and decreased dryness with green to blue. Coloured regions show where more than 10 out of 15 models (>66%) agree on which way soil moisture will change (grey shading elsewhere). Credit: IPCC 2012.

on model estimates and boreal summer evaluations (e.g. Koster *et al.* 2006). Our findings imply that with enough data, scientists could improve the prediction of very hot days or heat waves over a large part of the Earth's land surface, in both hemispheres.

Compare and contrast

We can compare two neighbouring regions, northern and southern Europe, to further illustrate the role of land-surface moisture conditions for temperature extremes (see Figure 2). Northern Europe is less sensitive to any shifts in soil moisture: that means that the region's total numbers of hot days don't really change, no matter whether the few months leading into the hottest summer months have been wetter or drier than usual. Meanwhile, southern Europe is more sensitive to shifts in soil moisture: the region gets a lot more hot days or cools more dramatically when the months leading up to summer are drier or wetter, respectively.

Southern Europe is what we would call a soil-moisture-limited evapotranspiration regime, and is a transitional region between wetter and drier climates overall. Meanwhile, northern Europe has a radiation-limited evapotranspiration regime, where soils are moister in general and sunlight (or lack thereof) drives changes in water levels in soil through evaporation.

But with climate change, regional sensitivities to soil moisture might change in ways we have yet to explore – in part because climate change could lead to changes in dryness (e.g. Seneviratne *et al.* 2006). Global climate models show that some regions might get wetter, while others dry out (see Figure 3). Although these projections remain ambiguous for now in most regions, models show consistently that some places like the Mediterranean are getting drier with warming global temperatures (Seneviratne *et al.* 2012, Orlowsky and Seneviratne 2012).

We need more data and a better understanding of relevant feedbacks and mechanisms within the climate system to assess more precisely what could happen in the future with droughts and climate extremes. One step forward will be an assessment of how soil moisture conditions have responded to past anthropogenic emissions that drive climate changes, and how they are likely to respond to future emissions.

The feedbacks identified in our work are a first step in this direction. These feedbacks also provide new angles for better seasonal forecasting of temperature extremes and the knowledge we will need to adapt to future climate changes.

With climate change, regional sensitivities to soil moisture might change.

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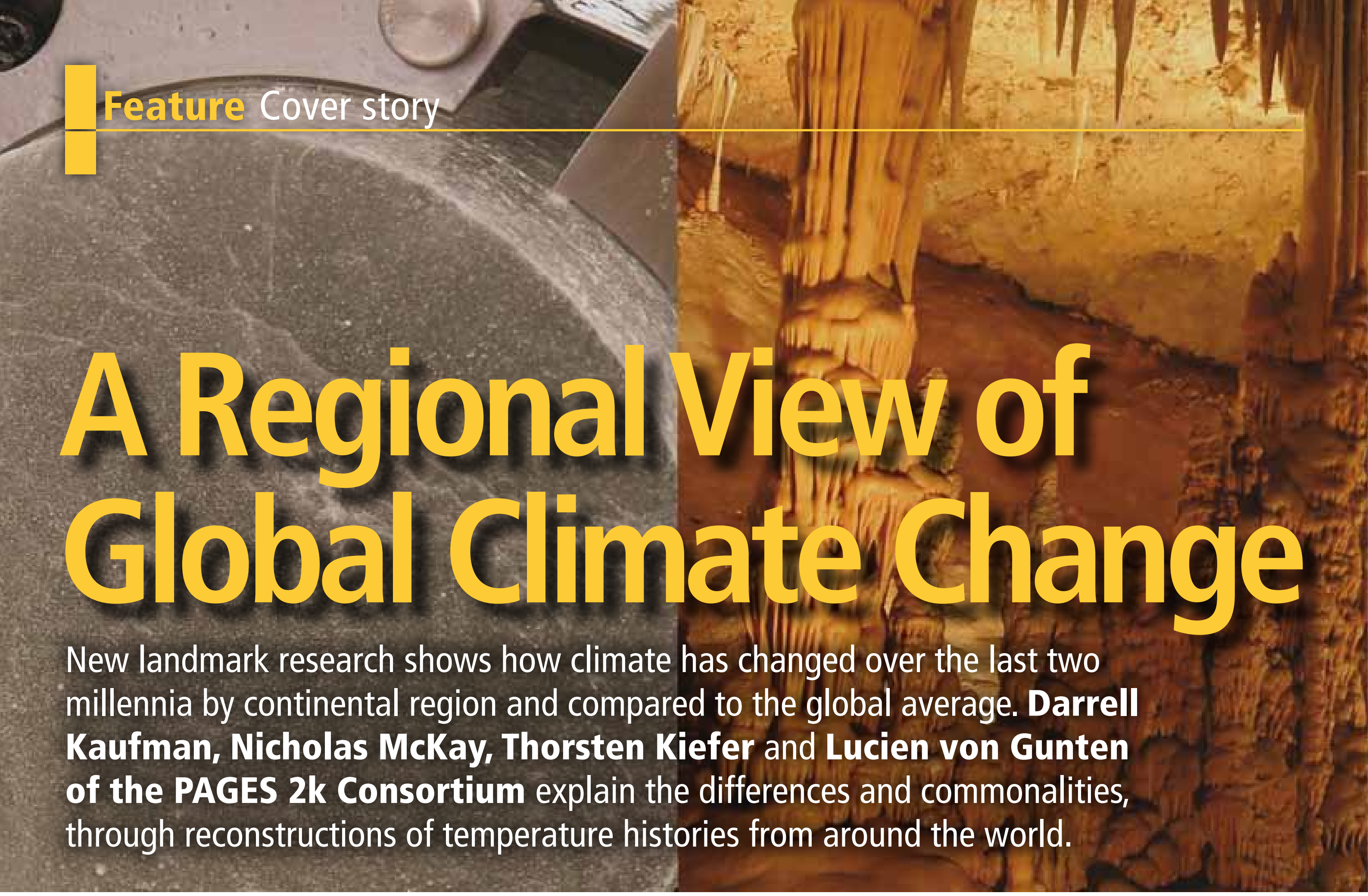

A Regional View of Global Climate Change

New landmark research shows how climate has changed over the last two millennia by continental region and compared to the global average. **Darrell Kaufman, Nicholas McKay, Thorsten Kiefer** and **Lucien von Gunten of the PAGES 2k Consortium** explain the differences and commonalities, through reconstructions of temperature histories from around the world.

In the year 1258 common era (CE), explosive eruptions from one or more unidentified volcanoes injected a vast amount of dust and acidified steam high into the atmosphere. The veil of particles impeded the Sun's rays for years, triggering the expansion of Arctic sea ice and leading to further cooling in the Arctic.

Lakes froze harder and longer in the Arctic during the 1260s, when temperatures dipped about 0.3°C lower than the average temperature of the last millennium. Algal production diminished in the lakes.

Meanwhile, halfway around the world in South America, trees thrived as growing-season temperatures increased by 0.3°C compared with the long-term average. At the same time, offshore of Australia, corals experienced higher surface ocean temperatures, a similar warming story recorded in their calcium carbonate layers.

On average, the planet was cooling at the time. But here were regions on the Earth experiencing that global average in opposite ways.

Climate scientists tend to talk about a warming planet: the average global temperature is on the rise, as greenhouse gas emissions swiftly heat up the Earth's atmosphere. But it turns out that different regions on Earth respond differently, perhaps lagging or speeding ahead, depending on where they are situated relative to global-change–driven shifts in atmospheric circulation and ocean currents. A new view of regional temperature records over the past two millennia illustrates just how each continent has varied along with past global climate changes.

Complex feedbacks

Put simply, Earth's climate is determined by the amount of incoming and outgoing radiation. But the details get complex: long-term cycles in the Earth's orbit, fluctuations in the Sun's output, and changes in the concentration of greenhouse gases and aerosols all influence the Earth's energy balance globally. However, these global-scale changes do not translate uniformly around the Earth; the atmosphere, oceans, and other components of the climate system redistribute energy in complex ways. The cause of global climate change might be geographically uniform, but its response is jumbled.

Climate scientists want to better understand how changes to the global energy balance, such as a changing greenhouse effect, are manifested in climate changes at regional scales, where they actually matter to people. A better understanding of the underlying processes will be important as we prepare for the plausible range of future changes from a combination of anthropogenic and natural drivers. The only way to investigate processes that operate over centuries or longer is to reconstruct past climate variability over space and time.

We know the most about recent climate changes, documented after the advent of precise instruments that track temperature, precipitation and more. But climate also varies naturally on long time scales, and going a century or more back in time quickly moves beyond the instrumental record. Fortunately, natural archives and historical documents offer indirect evidence, or proxies, of past climate variability; palaeoclimate researchers can tap those records to extract information about past climate changes.

PAGES 2k Network

In 2006, IGBP's Past Global Changes project (PAGES) began to set up the 2k Network, with the goal of compiling and analysing a global array of regional climate reconstructions for the last 2000 years. The network focused on the last two millennia because a sufficient number of proxy data records cover that timeframe in many regions; plus, fundamental features of the climate system, like the

From left to right: Ice core, speleothems, coral, tree rings

Photographs: US National Ice Core Laboratory; © iStockphoto.com/Joshua Haviv, Claire Desjardins, Sandramo

amount of glacier ice on Earth and sea levels, were similar to those of recent conditions, simplifying the interpretation of long-term climate changes.

The PAGES 2k Consortium is composed of 78 regional experts from 24 countries, representing 8 continental-scale regions. These experts culled through the proxy records available from individual sites, identifying which were best suited specifically for reconstructing temperature variability within their region (Figure 1). The resulting PAGES 2k dataset includes 511 individual time series from various archives. Most of the information comes from the analysis of tree rings, and the rest from ice sheets and glaciers, speleothems, corals, pollen, sediments from lake and ocean bottoms, and historical documents.

Each of these archives records temperature in different ways, many by individual years. The analytical methods for reconstructing past temperature from physical or biological properties are well established. For example, mud accumulates at the bottom of lakes, trapping the remains of algae and insects. Temperature changes affect the precise chemical make-up of the algal cell walls or the dominant species type of larval midges, providing a record that can be interpreted in terms of past temperature changes.

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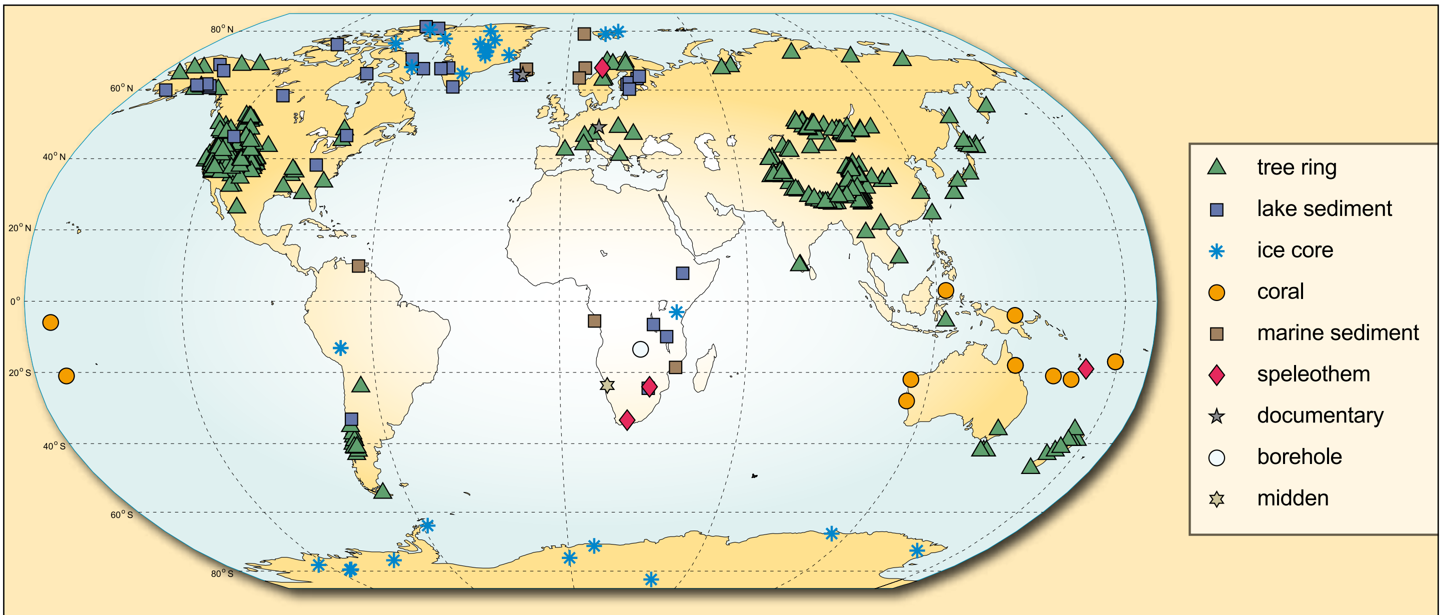
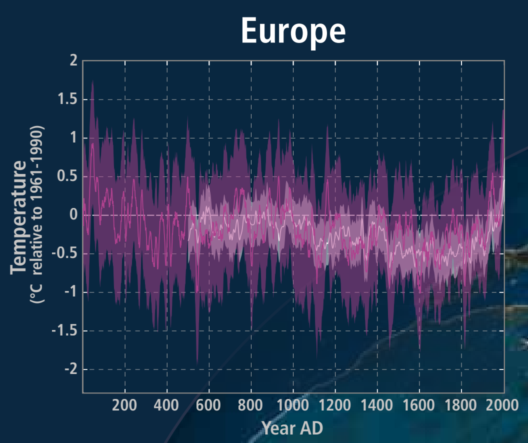
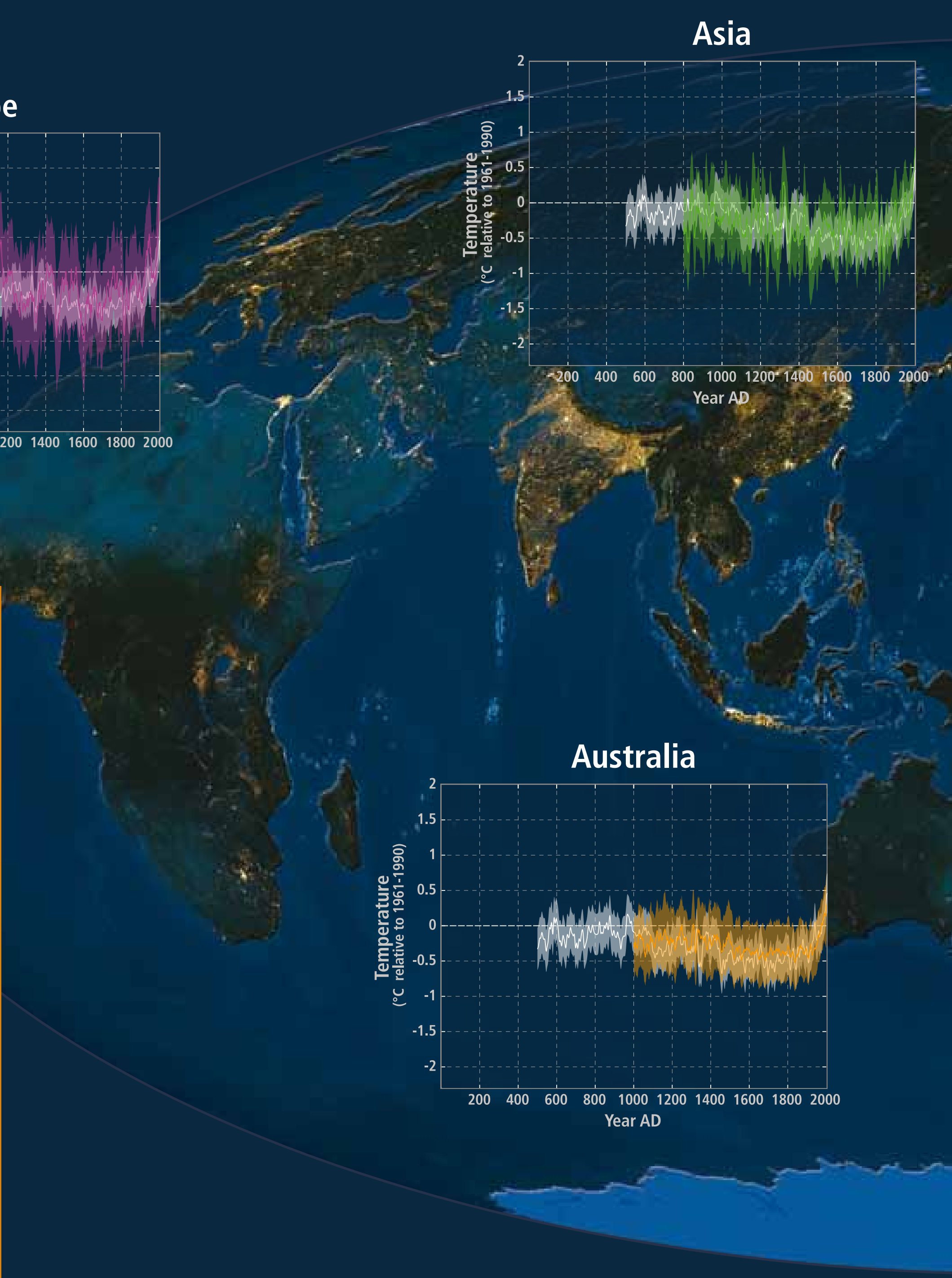


Figure 1. The regional PAGES 2k temperature reconstructions are based on the proxy record sites and types mapped here (with the exception of those from Africa, where there were too few sufficiently good temperature records).

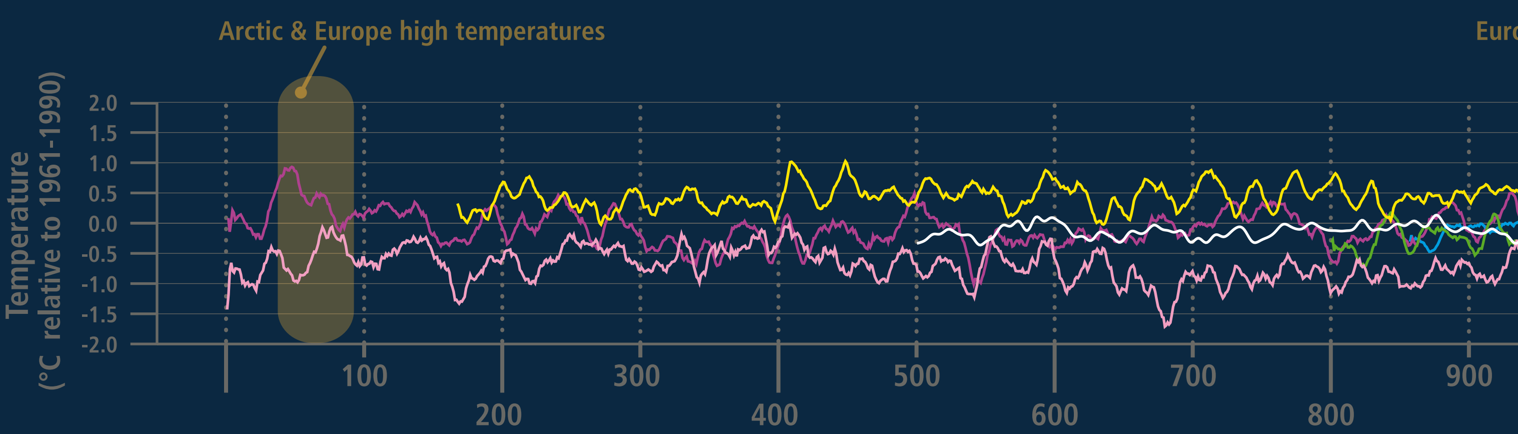




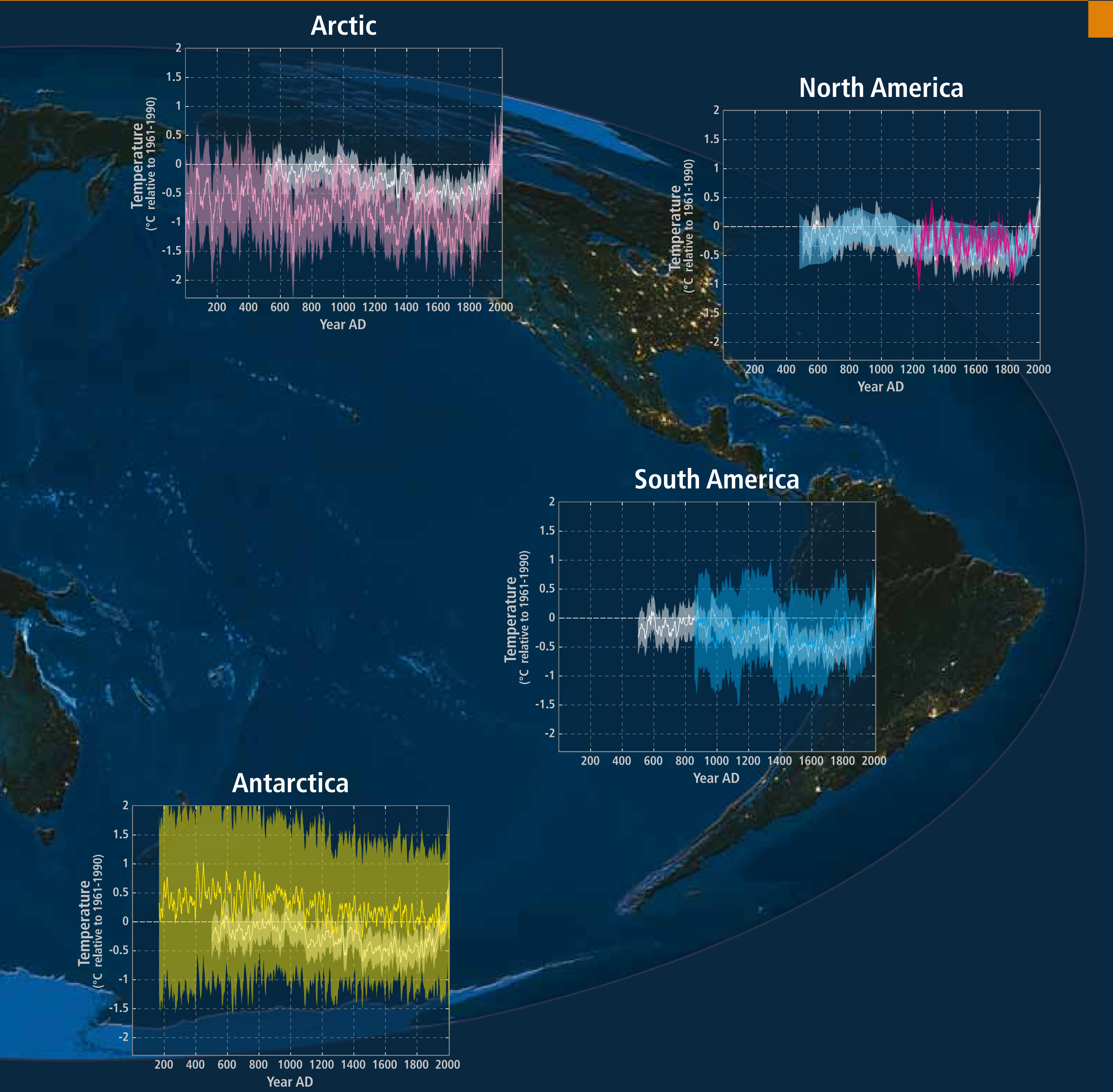
LOCAL VIEWS OF THE PLANET'S CLIMATE

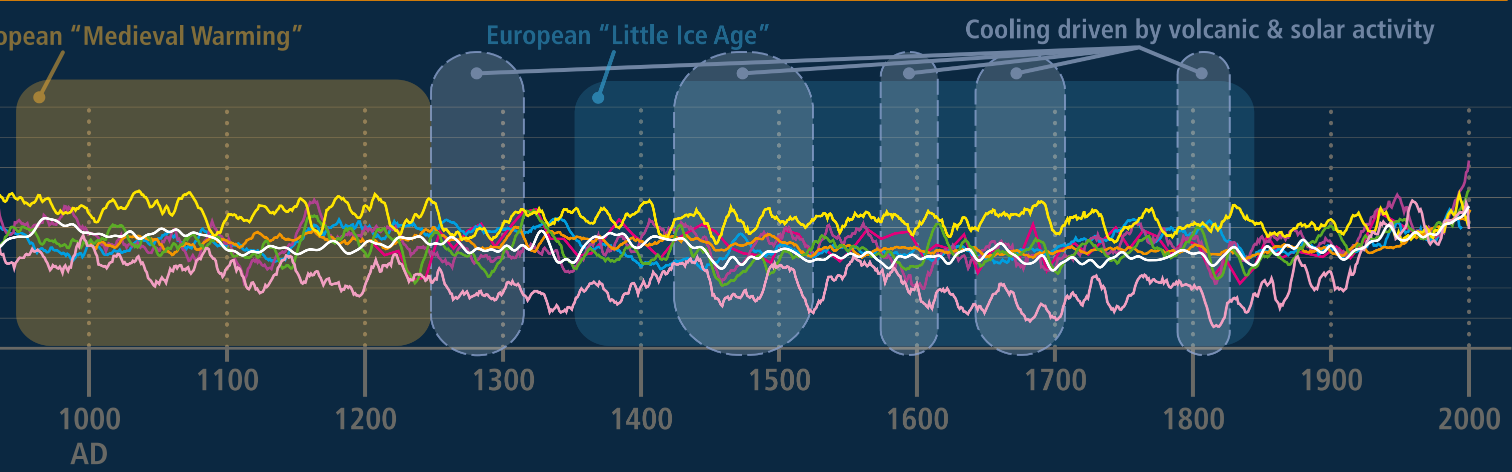
Each region of the planet has its own response to forces that change the Earth's climate as a whole, as highlighted by a synthesis from the PAGES 2k Consortium (see feature, p. 18). In the 2000-year temperature histories shown here, the coloured lines show the anomalies in temperature for each region, compared to a 30-year reference period, from 1961 to 1990 (uncertainties are indicated in a lighter shade). For comparison, the same global average appears in each region's graph as a white line, with uncertainties shown in grey (based on calculations by Michael Mann and colleagues). North America includes a temperature record derived from pollen in aqua.

For more information in addition to the feature in this issue, see the PAGES 2k Consortium's publication in *Nature Geoscience* (doi:10.1038/NGEO1797).



PAGES 2k Regional Temperature Reconstructions





MAPS: Félix Pharand-Deschênes, Globaïa; PAGES 2k Consortium

Continued from page 19

From these archives, the PAGES 2k Consortium reported the most comprehensive evaluation to date of temperature change at the surface of Earth's continents, over the past one to two millennia. The result is the first major synthesis product of the PAGES 2k Network, published last May (*Nature Geoscience*, doi:10.1038/ngeo1797).

Previous studies have focused on temperature reconstructions over the Northern Hemisphere, or they considered the planet as a whole. These perspectives are useful for understanding overall average conditions, but not for recognising important differences at the regional scale. In particular, the new synthesis includes temperature reconstructions from Antarctica, Australasia and South America, which clarify the poorly documented temperature history for Southern Hemisphere continents.

The specific timing of peak warm and cold intervals varied regionally.

Millennial-scale cooling

The most coherent feature in nearly all of the regional temperature reconstructions is a long-term cooling trend, which ended late in the 19th century. The cooling was slow – between about 0.1 and 0.3°C over 1000 years – but detectable in the PAGES 2k proxy climate datasets. A preliminary analysis using a climate model indicates that the overall cooling was caused by a combination of factors, including a decrease in solar irradiance and an increase in volcanic activity, as well as changes in land cover and slow changes in the Earth's orbit. The climate-model simulations also suggest that each factor was more or less important in different regions.

A recent reconstruction of average global temperature stretches further back, over the past 11,300 years (Marcott *et al.* 2013). These researchers focused mostly on proxy records from marine sediments, which usually have a resolution at the scale of centuries. That study's data thus are based on a very different foundation from that of PAGES 2k, but one that places the PAGES 2k reconstruction independently in the context of even longer-term trends (Figure 2). When averaged among the continental-scale regions, the cooling trend prior to the 20th century detected in the PAGES 2k study agrees with Marcott and his colleagues' longer-term record.

Regional variability

The long-term cooling trend casts new light on the classical view of a Medieval Warm Period followed by a colder Little Ice Age. Scientists have had a hard time pinning down the onset and end of these two intervals with any consistency: they seemed to have occurred at different times in different places. The PAGES 2k mapping of temperature changes across the globe delivered proof that temperatures did not fluctuate uniformly among all regions (Figure 3).

At longer multi-centennial scales, all regions were generally warmer earlier and then cooled, but there were no globally synchronous multi-decadal warm or cold intervals that define a worldwide Medieval Warm Period or Little Ice Age. Instead, the specific timing of peak warm and cold intervals varied regionally, with multi-decadal variability resulting in regionally specific temperature departures from an underlying global cooling trend.

The temperature fluctuations during the last one to two millennia were more uniform within the hemispheres than between them. In the Northern Hemisphere, the period from around 850 to 1100 CE generally was warmer. In contrast, in South America and Australasia, a sustained warm period occurred later, from around 1160 to 1370 CE. Similarly, the transition to colder regional climates between 1200 and 1500 CE is evident earlier in the Arctic, Europe and Asia than in North America or the Southern Hemisphere.

Recent warmth

The 20th century ranked as the warmest in all regions except Antarctica. During the last 30-year period in the PAGES 2k reconstructions (from 1971 to 2000), the average reconstructed temperature of all of the regions was likely the warmest in nearly 1400 years. However, temperatures in some regions were higher in the past than they were during the late 20th century. The longer

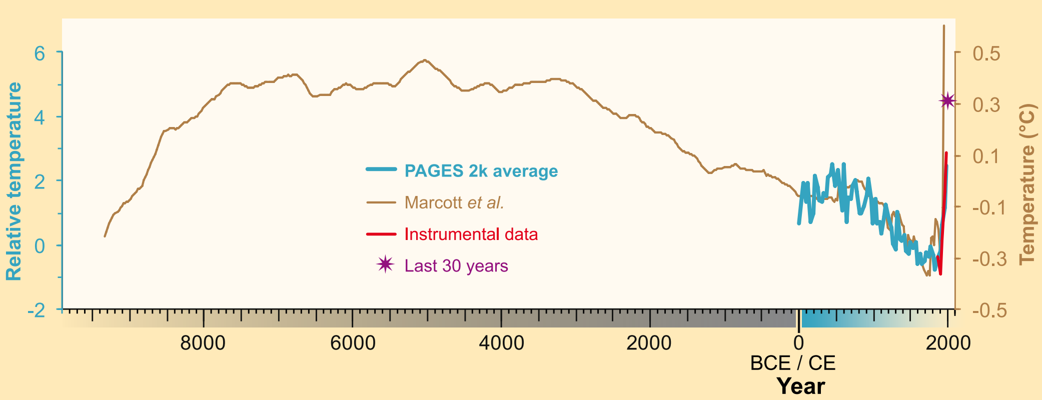


Figure 2. The average of all seven PAGES 2k regional relative temperature reconstructions (aqua; see Figure 3) compared to the recently published global temperature reconstruction that extends back 11,300 years (brown). Annual global temperatures from the HadCRUT4 instrumental dataset are shown for reference, as a time series (red). A star marks the average temperature of the most recent 30-year period (1983–2012).

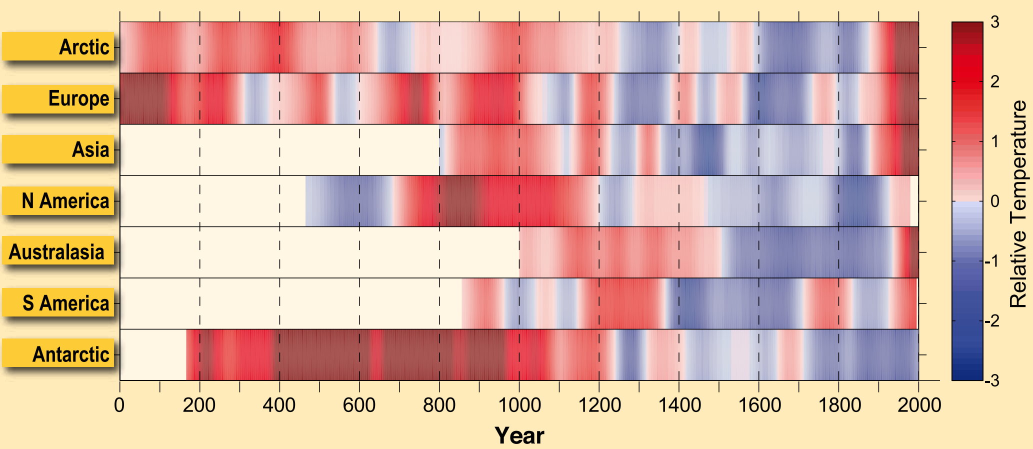


Figure 3. Temperature changes in the seven PAGES 2k continental-scale regions, arranged in rows from north to south. Colours indicate the relative extent to which temperatures were warmer (red) or cooler (blue) than the average from 1200–1965, the period of overlap for the seven reconstructions. The most prominent feature of nearly all of the regional temperature reconstructions is the long-term cooling that ended late in the 19th century. On shorter time scales (decades to centuries), temperatures did not fluctuate uniformly among all regions.

the individual site record, the more likely it would show prior warm intervals, which is expected for an overall cooling trend such as found in the PAGES 2k reconstructions, and in the longer 11,300-year reconstruction. In Europe, for example, the average temperature between 21 and 80 CE (two millennia ago) was warmer than during 1971 to 2000.

But these localised warm periods of the past do not suggest that the recent average global warming of the past few decades is part of a natural cycle. Figuring out whether the temperature change is unprecedented (which it is not entirely) is not the same as determining whether it is influenced by humans (which it almost certainly is).

The increase in average temperature for all of the PAGES 2k regions between the 19th and 20th centuries exceeded the temperature difference between all other consecutive centuries in most regions (note the pronounced blue-to-red shift towards the right in Figure 3). The global warming that occurred in the 20th century reversed a long-term global cooling trend. This pre-industrial cooling trend was likely caused by natural factors that continued to operate through the 20th century, making the 20th century warming difficult to explain without the impact of increased greenhouse gases from anthropogenic emissions.

Regional shifts in global trends

Like the atmosphere that envelops our planet, Earth's climate is a global system, but it's the smaller-scale features of climate that most directly influence human and ecological systems. Understanding how changing climate affects a particular region requires both a global view of the climate system and the collective local knowledge of collaborating scientists from around the world.

The PAGES 2k reconstructions have shown clear regional expressions of temperature variability at the multi-decadal to century scale, whereas a long-term cooling trend prior to the 20th century is evident globally, as a backdrop to these regional pictures. These findings point to the necessity of understanding local differences for a truly global view, and the next steps of PAGES 2k will be to refine the temperature reconstructions and add a history of regional precipitation changes. The data assembled for this first synthesis are available for downloading through the NOAA Paleoclimatology World Data Center, and will no doubt be analysed for years to come, using alternative approaches to reveal other patterns and address further research questions through the PAGES 2k Network and beyond.

Understanding local differences for a truly global view.

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The PAGES 2k CONSORTIUM represents 78 scientists of the PAGES 2k Network who made an active contribution to the temperature history paper in *Nature Geoscience*.

PAGES is sponsored by the US National Science Foundation, US National Oceanographic and Atmospheric Administration and Swiss National Science Foundation.

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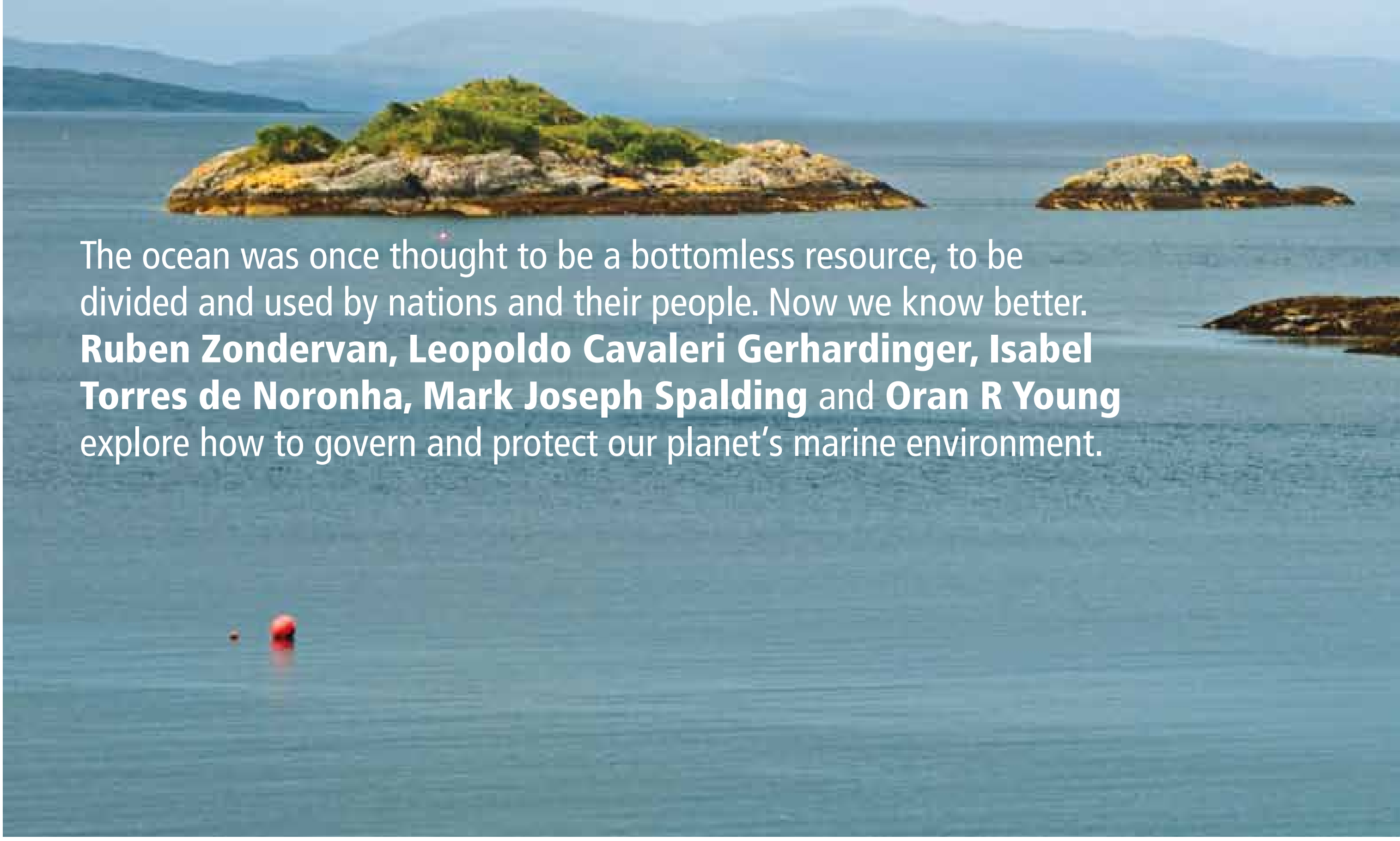
OCEAN GOVERNANCE IN

The ocean was once thought to be a bottomless resource, to be divided and used by nations and their people. Now we know better. **Ruben Zondervan, Leopoldo Cavaleri Gerhardinger, Isabel Torres de Noronha, Mark Joseph Spalding** and **Oran R Young** explore how to govern and protect our planet's marine environment.



We humans once thought the Earth was flat. Little did we know that the oceans extended far beyond the horizon, covering about 70% of the planet's surface, containing more than 95% of its water. Once early explorers learned that planet Earth is a sphere, the oceans morphed into a huge two-dimensional surface, largely uncharted – a *mare incognitum*.

Today, we've tracked courses across every sea and plumbed some of the ocean's greatest depths, coming to a more three-dimensional perspective of the water that envelopes the planet. We now know that the interconnectedness of these waters and systems means that Earth truly has only one ocean.

While we have yet to comprehend the depth and seriousness of the threats posed by global change to our planet's marine systems, we know enough to recognise that the ocean is in peril as a result of overexploitation, pollution, habitat destruction and climate change impacts. And we know enough to acknowledge that existing ocean governance is woefully inadequate to address these threats.

Here, we define three major challenges in ocean governance, and then frame the five analytical governance problems that need to be addressed, according to the Earth System Governance Project, in order to protect Earth's complex interconnected ocean.

Laying out the challenges

Here, we consider three priority challenges in ocean governance: the rising pressures on, the need for enhanced global coordination in governance responses for, and the interconnectedness of marine systems.

The first challenge relates to the need to govern the increasing human uses of marine systems that continue our overexploitation of the ocean's resources. The ocean is the perfect example of how universal goods can be exhausted even when some protective rules are in place, whether formal laws or informal community self-governance.

Geographically, each coastal nation state has sovereignty over its own coastal waters. But beyond national waters, marine systems include the high seas and the seabed, which come under the United Nations Convention on the Law of the Sea (UNCLOS), established in 1982. The ocean seabed and waters beyond national jurisdictions most often do not lend themselves to informed community self-governance; thus, laws that apply penalties under these circumstances could be more useful to stemming overexploitation.

Cases of maritime commerce, marine pollution, and migratory species and border-crossing fish stocks demonstrate that many issues cut across boundaries of the waters of coastal states and the high seas. These intersections generate a second set of challenges, which require coordination between individual coastal nations and the international community as a whole.

Marine systems also are interconnected with atmospheric and terrestrial systems. Greenhouse gas emissions are changing Earth's biogeochemical cycles and ecosystems. Globally, ocean acidification and climate change are the most important consequences of these emissions. This third set of challenges requires governance systems capable of addressing connections between major components of Earth's natural systems in this time of significant and accelerating change.

Analysing the problems to tackle

The Earth System Governance Project is taking steps to address the three major challenges we present above. Started in 2009, the decade-long core project of the International Human Dimensions Programme on Global Environmental Change brings together hundreds of researchers around the world. With the help of a task force on ocean governance, the project will synthesise social science research on themes relevant to our challenges, including regime fragmentation; governance of areas beyond national jurisdictions; fisheries and mineral resource extraction policies; and the role of trade or nongovernmental stakeholders (such as fishermen or tourism businesses) in sustainable development.

The task force also will develop the project's research framework, which prioritises five interdependent analytical problems within the complex issues of ocean governance. Let's skim through these briefly.

The first problem is the study of overall governance structures or architecture related to the ocean. The "constitution of the ocean", UNCLOS, lays out the overall terms of reference for ocean governance. Key aspects of UNCLOS include the delimitation of maritime jurisdictions, how nation states should interact with each other, and overall objectives of ocean management, as well as assigning specific responsibilities to intergovernmental organisations.

But this system has become outmoded as humans have become more efficient than ever at harvesting marine resources, and human uses of marine systems (such

THE ANTHROPOCENE

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Marine mix: a sampling of international, national and regional government bodies, nongovernmental organisations, researchers, businesses and others that participate in ocean governance issues.

as oil drilling, fisheries, coral reef tourism and marine protected areas) now overlap and clash. Above all, the system has failed to address the unintended impacts of human activities on the ocean from land and air interactions: anthropogenic greenhouse emissions.

The second analytical problem is that of agency. Today, the ocean and other Earth systems are affected by intergovernmental bureaucracies, local or community-level governments, public-private partnerships and scientific networks. The oceans are also affected by purely private actors, such as large companies, fishermen and individual experts.

Historically, such nongovernmental groups, and in particular hybrid public-private partnerships, have had strong influence on ocean governance. For example, the Dutch East India Company, established in 1602, was granted a monopoly on trade with Asia by the Dutch government, as well as authority usually reserved for states, including the mandate to negotiate treaties, coin money and establish colonies. In addition to its state-like powers over marine resources, the company was first to share its profits with private individuals.

The Earth System Governance Project is taking steps to address the three major challenges.

Today, private investors are lining up to harvest natural resources for pharmaceuticals and conduct deep-seabed mining, hoping to profit from what should be considered a universal good. These examples and others make it clear that ocean governance can play a role in levelling the playing field.

The third problem is adaptiveness. This term encompasses related concepts that describe how social groups respond to or anticipate challenges created through environmental change. These concepts include vulnerability, resilience, adaptation, robustness, and adaptive capacity or social learning. A governing system must be adaptive itself, as well as govern how adaptation happens. For example, while the pollock fishery in the Bering Sea has adapted to climate change by moving north, the US and Russian governments seemingly have not: the two nations argue over fishing rights based on geographic location of the fishery and disputed borders of their coastal waters.

Fourth is accountability and legitimacy, not only in political terms, but also in a geographical sense for the ocean: these waters are beyond the nation state, open to all and belonging to none. But **one** ocean implies the interconnectedness of geography and water masses, peoples, and natural living and inanimate resources. These interconnections place additional demands on problem-solving processes, to deal with diverse stakeholders' capabilities, responsibilities and interests.

An example is a recent 'rogue' ocean fertilization experiment at the Canadian coast, where a private company seeded ocean waters with iron to increase carbon sequestration. This was widely reported as an unregulated 'geoengineering' experiment. Who has the right to experiment with the ocean? And who can be penalised if something goes awry? These unfolding conflicts are feeding a thoughtful debate around accountability and legitimacy.

The final analytical problem is allocation and access. Who gets what, when, where and how? A simple bilateral treaty dividing the ocean to benefit two countries at the expense of all others never worked, as the Spanish and Portuguese discovered centuries ago.

After Columbus' explorations, the two countries entered into the 1494 Treaty of Tordesillas and the 1529 Treaty of Saragossa. But the maritime powers of France, England and The Netherlands largely ignored the bilateral division. Ocean governance at the time was based *de facto* on simple principles like "winner takes all", "first come, first served" and "freedom of the seas". Today, more sophisticated mechanisms are required to share responsibilities, costs and risks related to the ocean, as well as to give equitable access to and allocation of the ocean's services and benefits.

A new era in understanding

With a heightened awareness of the challenges at hand, natural and social scientists are seeking consilience for effective ocean governance. They also are engaging with stakeholders to conduct their research.

For example, IGBP's Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project is developing a framework called IMBER-ADapt to explore policy-making for better ocean governance. The recently established Future Ocean Alliance (FOA) also brings together organisations, programmes and individuals to integrate specific disciplines and their knowledge, in order to improve dialogues on ocean governance and assist policymakers.

FOA's mission is to "use innovative information technologies to build an inclusive community – a global ocean knowledge network – able to address emerging ocean governance issues promptly, efficiently, and fairly". The alliance will seek to assist in the earliest stages of decision-making, to enhance the sustainable development of the ocean from the local to the global level. FOA brings together producers and consumers of knowledge and fosters collaboration among numerous organisations and individuals. Organisations include the UN Intergovernmental Oceanographic Commission; the Benguela Commission; Agulhas and Somali Currents Large Marine Ecosystem project; the ocean governance assessment of the Global Environment Facility Transboundary Waters Assessment Programme; the Land-Ocean Interactions in the Coastal Zone project; the Portuguese Directorate General for Ocean Policy; the Luso-American Foundation for Development; and The Ocean Foundation, among others.

Members of FOA, including the Earth System Governance Project, are exploring ways to contribute to the development of an ocean research agenda for the Future Earth initiative (see news story, p. 6). In the next decade, the Future Earth initiative will be an ideal platform to bring together researchers, policymakers and other stakeholders for developing solutions to marine problems.

Together, we can provide the knowledge and tools needed for effective ocean governance in the Anthropocene. This human-affected epoch is *mare incognitum* – an uncharted sea. As the complex natural systems in which we live change with human impacts, we don't know what will happen, particularly to Earth's ocean. But timely and adaptive ocean governance processes will help us to navigate the Anthropocene. ▮

Natural and social scientists are seeking consilience for effective ocean governance.

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The rise and fall of the ancient Maya has intrigued historians and archaeologists for decades. Now, Earth-system scientists are taking a keen interest. **Scott Heckbert** asks: what role might environmental conditions and trade play in the growth and eventual collapse of a civilisation?

LESSONS FROM A SIMULATED CIVILISATION

Classic Maya culture developed over millennia, peaked around 1300 years ago, and then abruptly "reorganised" within 200 years. A society of possibly 10 million people, living in an area the size of Great Britain, unravelled as destabilisation rippled through the Classic Maya world.

The fate of the Classic Maya triggers modern apocalyptic visions of empty cities, silent without the rush of cars and people, slowly reclaimed by flora and fauna – just as ancient Maya cities are now quiet and shrouded in thick vegetation. We hope that our own contemporary system is sufficiently resilient to avoid catastrophic change, but is it? Will our growing pressure on the Earth's systems lead us to a similar fate? And how can we tell?

We can view societies as complex systems with interacting social and ecological components. Computer models can illuminate some of the interactions that occur within these social-ecological systems. We can use these computer models to explore the underlying conditions for sustainability or collapse.

Using the ancient Maya civilisation as an abstract example, we developed a new model called MayaSim for a project with the Integrated History and future of People on Earth (IHOPE) initiative (Heckbert *et al.* 2013, Heckbert 2013, ihopenet.org). IHOPE is sponsored by the International Human Dimension Programme and the IGBP and two of its core projects, Past Global Changes (PAGES) and Analysis, Integration and Modeling of the Earth System (AIMES).

At the heart of the MayaSim model is a society connected by trade relationships and environmental conditions. The virtual civilisation must navigate changing interactions between its social and environmental components to achieve long-term sustainability – or not.

Health diagnoses

A medical doctor assesses a patient's health by examining their digestive, circulatory, musculoskeletal, immune and other systems; each functions alone, but all are connected to each other within the overall "body system".

Similarly, historians and archaeologists might examine a society by its systems. A society uses systems to acquire materials and energy from the environment, and for production and distribution. Other systems include the arrangement of physical structures such as cities and trade routes, its demographic trends, and how these in combination respond to adverse conditions or shocks.

Researchers can collect data and create integrated models of how social-ecological systems work. These models can be tested against the historical record through simulations, and eventually might provide guidance for social-ecological resilience and health.

Modelling the Maya

The MayaSim model represents the ancient Maya social-ecological system in space and time. The contours of the Yucatan Peninsula, the mountains and valleys, forests and waterways are represented in a grid of cells including GIS data for soil, topography, rainfall and temperature. Individual human settlements are "agents" in the model. Settlements establish trade with neighbouring settlements, creating networks across the landscape.

In the model, the agents, cells and networks are programmed according to their social and ecological functions. Social functions – demographics, trade, and agriculture – interact with each other and with environmental characteristics – soil degradation, ecosystem services, climate variability, hydrology, primary productivity and forest succession. (Model code and results are available online; see Heckbert 2013.)

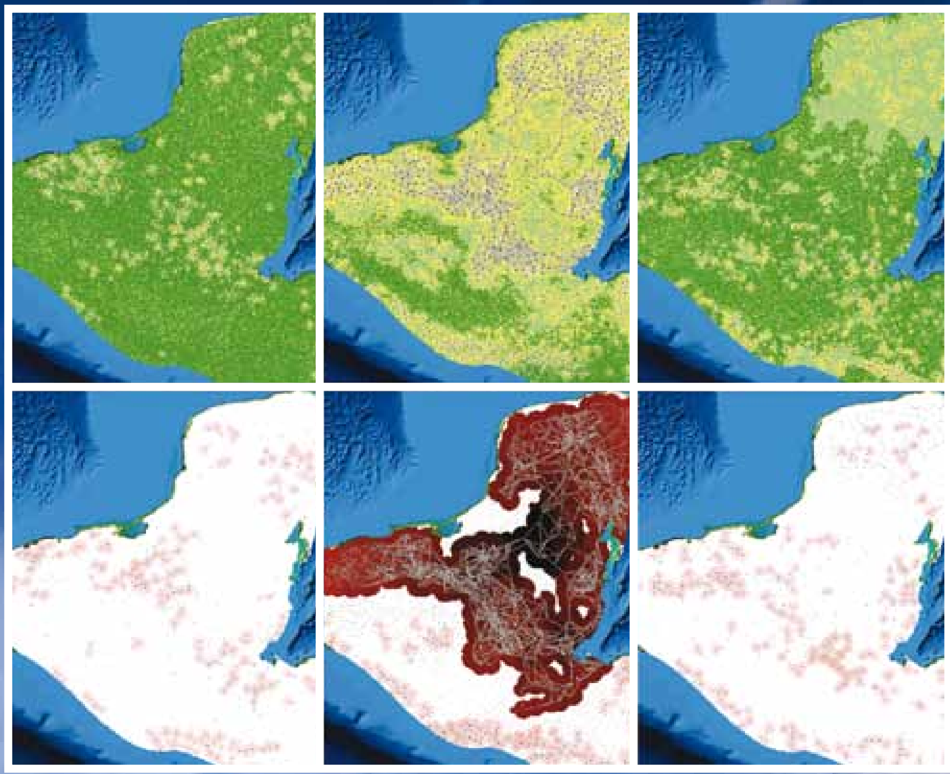
The model begins with a pristine natural environment. Environmental and human systems progress together through time, effectively growing the social-ecological system from the bottom up. This artificial social-ecological laboratory allows different theories to be tested, such as how different patterns in forest harvesting, rates of soil productivity loss, and development of trade networks affect overall sustainability.

Historic footsteps

Archaeologists have defined a timeline for the ancient Maya (specifically the Lowland Maya of the Yucatan Peninsula) based on patterns of regional growth. They identify the pre-Classic (1000 Before Common Era, or BCE, to 250 Common Era, CE), Classic (250–900 CE), and post-Classic periods (900–1500 CE).

The Classic Maya culture reached its height around 700 CE, a time when Maya society built many of its most impressive monuments and increased its socioeconomic connectivity. At the end of the Classic period, the population of the Maya lowlands had reached an order

Figure 1. Snapshots over time from the MayaSim model show changes in forest cover (upper row) and the configuration of trade networks (lower row). Cleared and agriculturally cultivated cells are yellow, secondary regrowth is light green, and climax forest is dark green. Darker red colouring shows higher wealth gained from trading. The Maya civilisation might have looked like these model snapshots at roughly 800 BCE, 800 CE and 1600 CE, respectively.



of magnitude larger than the region supports today, with some estimates of up to 10 million people. Temple IV at Tikal (nearly 65m in height), the tallest building in the pre-Columbian Americas, was constructed in 747 CE, during the height of the Late Classic period. The last monument at Tikal was erected in 869, and the site effectively was abandoned less than 100 years later. The largest building in present-day Belize is still the main Maya architectural complex of Caana at Caracol, abandoned around 900 CE.

Somehow, a rapid and fundamental transformation altered this civilisation's political, social, economic and demographic organisation. Explanations for what is commonly referred to as the Classic Maya Collapse (e.g., Culbert 1973) include extended droughts, greedy rulers, foreign influences, deforestation and fatalism, among others (e.g., Aimers 2007). The crisis led to the abandonment of many small, medium-sized and large cities, some of which supported up to 80,000 to 100,000 people (Turner and Sabloff 2012).

MayaSim can reproduce spatial patterns and timelines somewhat analogous to that of the ancient Maya's history. As the model steps through time, we can watch small settlements expand into cities and major trading locations, and how this development can consume forests and soil productivity, eroding natural capital.

Snapshots from MayaSim show that by 250 BCE in the model, settlements have popped up in all regions of the model's landscape, first occupying areas with greater ecosystem services and growing with agricultural development. Population densities are higher in areas where settlements have clustered and formed local trade connections. By 500 CE, as the value of trade increases, population dramatically increases in the model. Local trade connections reach

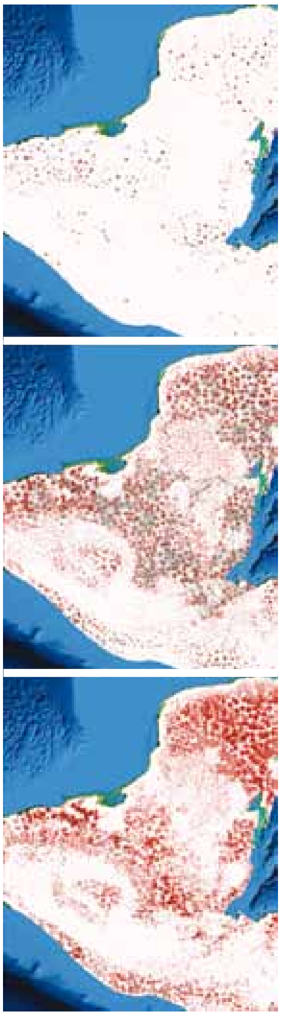


Figure 2. Soil degradation in the simulated MayaSim landscape at 800-year intervals shows initial use (top), peak degradation (middle), and degradation remaining during waning use (bottom) after populations and trade routes collapse (greater degradation is darker red). The years of the snapshots from the simulation are the same as in Figure 1.

across the entire landscape, creating 'global' connectivity.

MayaSim's modelled centre of the trade network emerges in the region where the ancient Maya capitals of Tikal, Calakmul and Caracol existed. As development reaches its height in the model, the condition of the forest changes markedly: only small patches of mature forest remain in agriculturally unsuitable areas, forming ecological refugia for flora and fauna within a landscape that is nearly completely settled by people (just as it might have at the height of the Classic Maya in 700 CE).

Jumping forward in time, by 1500 CE, the modelled trade network has disintegrated, and the centre of the most densely populated areas is nearly entirely abandoned. Only a small number of locally connected settlements remain at what was once the fringe of the regionally connected network. As population levels fall, the model shows abandoned cropland and significantly decreased forest harvesting. The change allows widespread revegetation, and mature forest eventually expands from its refugia.

Model crossroads

MayaSim reports metrics that explain this pattern of development and reorganisation. One such metric is "real income" as an abstract measure of economic value. In the first quarter of the simulation run, ecosystem services provide the majority of real income for the settlements. By 500 BCE, ecosystem services values are superseded by agriculture, and both are superseded by trade around 250 CE. Trade's increased value can be explained by the larger connectivity of the trade network in the model, allowing settlements to specialise their local production systems as the network grows from local clusters to a nearly completely connected system in MayaSim.

Human populations grow in the model as real income per capita increases, particularly from gains derived from trading. In turn, agricultural development increases to feed these extra people, but with a relatively smaller gain in overall yield per hectare. The limited increase in food production signals that marginal lands get put to use to feed these growing populations.

Land use connects to other quantifiable metrics. We see that natural capital reaches its lowest level in the model at the same point in time as the peak in human populations and built infrastructure.

Natural capital is represented in part by the condition of the forest in the model: early on, cropping and timber harvesting for construction and fuel wood consume mature forest and inhibit forest regrowth. Then, in roughly the second third of the simulation run, growing human populations result in marginal lands being put to agricultural use, even as forest regrowth continues to lag. As a result, the rate of soil degradation – another important metric – peaks during this period. The last third of the simulation run shows a rapid decline in cleared and cultivated land as population decreases; large-scale revegetation ensues, and eventually, the mature forest recovers to near pre-development levels.

Even though natural capital recovers to some extent at this point, the loss of soil productivity limits future resettlement opportunities. The trade network structure is gone, and without that trade value, human populations do not recover.

What went wrong?

A key finding of the MayaSim model is how processes across different scales combine to contribute to sustainability or collapse, from individual cells and settlements to the whole society connected via trade networks. For example, the trade network grows to become a "global" structure across the whole landscape; an individual settlement node in the network represents mesoscale processes, such as agricultural management and demographics; individual cells on the landscape represent microscale processes. Each scale contains fast and slow variables of change: for example, deforestation occurs quickly, while soil regeneration is extremely slow. Trade value can change rapidly, while demographics can lag behind several years.

The model features apparent "collapse traps" into which the social-ecological system can fall, which results in system collapse. One such trap is a trade system that is hyperinflated for too long, which significantly degrades soils in marginal lands. A cross-scale effect occurs when a critical node in the overall trade network exhausts productivity of its local marginal lands and food production drops at that location. The settlement's population can decrease and trade connections can be broken, affecting the entire trade network. This change can ripple out to other settlements, causing a cascading failure in the network.

Connecting trade to marginal lands and soils is perhaps not initially intuitive. However, when all the social-ecological building blocks are connected, we can see patterns of change embedded in each subsystem that contribute to macroscale system patterns.

Collapse traps

In MayaSim, collapse results from cascading trade network failure. A series of underlying conditions at the meso- and microscales contributes to this failure. We tested the model to see if anything might help to avoid these collapse traps, with a series of interventions such as soil conservation, forest management, population control and limits to trade value. We found that combinations of interventions can affect the results generated by the model.

The findings suggest that in this complex system, no single intervention prevents collapse. It takes at least three system interventions (for example, targeting soil, forests and population growth) to stabilise the system and achieve a sustainable outcome. However, in many instances, applying an intervention can have unintended consequences: the resulting modelled social-ecological system may never flourish, and remains limited to what might be interpreted as broad-scale swidden agriculture – temporary slash-and-burn farming. This system can also be viewed as sustainable, but does not achieve the heights in populations and built infrastructure we associate with the Maya. In applying interventions, balance is key to achieving both a sustainable and desirable outcome.

The final lessons from this research shed light on how we might measure resilience in today's real world. The MayaSim model itself is an abstraction, with little empirical data from the real ancient Maya to validate the results. However, the concept that dynamics in a social-ecological system can be quantified and simulated to generate patterns of sustainability or collapse is fascinating and worthy of further exploration.

Is it realistic to develop a similar model for our global civilisation? A tentative answer is yes. The MayaSim approach could explore contemporary social-ecological resilience and test theories for today's globally connected trade system by comparing trade network statistics and maps of natural capital at various points in a simulation run. We could use trade network statistics to identify vulnerable critical trade nodes. We could also compare the patterns in our contemporary human ecological footprint with trends observed in the model, and contrast rates of deforestation, soil degradation and population changes to identify any warning signs or hotspots where both trade vulnerabilities and degraded ecosystem services might ignite a cascading failure.

With respect to avoiding collapse traps in our modern society, a clear lesson is that our livelihoods are based largely on our trading connections. Trade introduces vulnerabilities but allows specialisation in an economy. We are all connected, and a perturbation in the trade network can start a cascading failure when the health of supporting subsystems has been compromised. ∎

A medical doctor assesses a patient's health... Similarly, historians and archaeologists might examine a society.

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Using the Planet

Even before the advent of agriculture, *Homo sapiens* kicked off an entirely new process of planetary change. Earth would never be the same. Instead of mere centuries, **Erle C Ellis** advances a broader view of the Anthropocene, over many millennia, and what that means for land stewardship.

Unlike prior geological time periods, the long-term driving forces of global change in the Anthropocene are not solely within the realm of physics, chemistry or even biology. The ultimate drivers of the Anthropocene are inherently social: *Homo sapiens* is able to create, pass on and spread adaptive technological and social innovations across individuals, generations and societies more effectively than any other species.

Human activities have led to global changes in Earth's atmosphere, climate, lithosphere and biosphere that are unprecedented in human history, if not the history of the planet. Recognition of these human-made shifts prompted the call for the Anthropocene as a new geological epoch, starting with the rise of the Industrial Revolution (circa 1850) or its "Great Acceleration" since 1950.

Yet the evidence from archaeology, palaeoecology and environmental history is clear: human societies have been reshaping the terrestrial biosphere, and perhaps even global climate, for millennia. The entire past 11,000-plus years of the Holocene might simply be renamed the Anthropocene (see the references below, in particular, Ruddiman 2013 and Smith and Zeder 2013).

Formal recognition of the Anthropocene is ultimately a decision for geologists. But global-change science has much to gain from a more geologic view of humanity's role in Earth system dynamics. By exploring how people have used land over many millennia, we can better understand the social processes that have made it possible for a single species to alter the course of Earth's history (Ellis 2011, Ellis *et al.* 2013).

Human societies have been reshaping the terrestrial biosphere, and perhaps even global climate, for millennia.

Land-use intensification

Humans and their land-use practices have profound and persistent effects over periods from centuries to millennia (Figure 1). Land clearing by hunter-gatherers and farmers, soil tillage, and wet rice production all emit major amounts of carbon dioxide and methane. As a result, early human use of land might have initiated global changes in climate long before human use of fossil fuels, beginnining as early as 7000 years ago, by gradually increasing methane and carbon emissions on the continents and shifting the baseline of global climate sensitivity to these emissions, according to evidence presented by Ruddiman (2013).

While this "Early Anthropocene" hypothesis remains an active area of research, understanding the role of early land use in determining both the onset and magnitude of anthropogenic climate change is necessary to evaluate the biosphere's role in both current and future climate change. That assessment includes the prospects for biofuels, as well as reduced deforestation and tillage to mitigate carbon emissions from fossil fuels. But global changes in climate are perhaps the least important effects of our ancient ancestors' land-use practices.

While landscapes with the most people using them tend to be the most altered, even the least intensively used landscapes have been transformed: rangelands and seemingly undisturbed areas near human populations tend to have exotic species, altered fire regimes, nutrient pollution and other pervasive human effects (Ellis 2011, Hobbs *et al.* 2013). Recognition of humans' huge and sustained influence is now leading to a wholesale rethinking of ecological science and conservation that moves away from humans as recent destroyers of a pristine nature and towards humanity's role as sustained and permanent stewards of the biosphere (Hobbs *et al.* 2013). But understanding that role requires understanding how humans have managed to sustain ever larger populations over millennia.

Broadly defined, land-use intensification is an adaptive

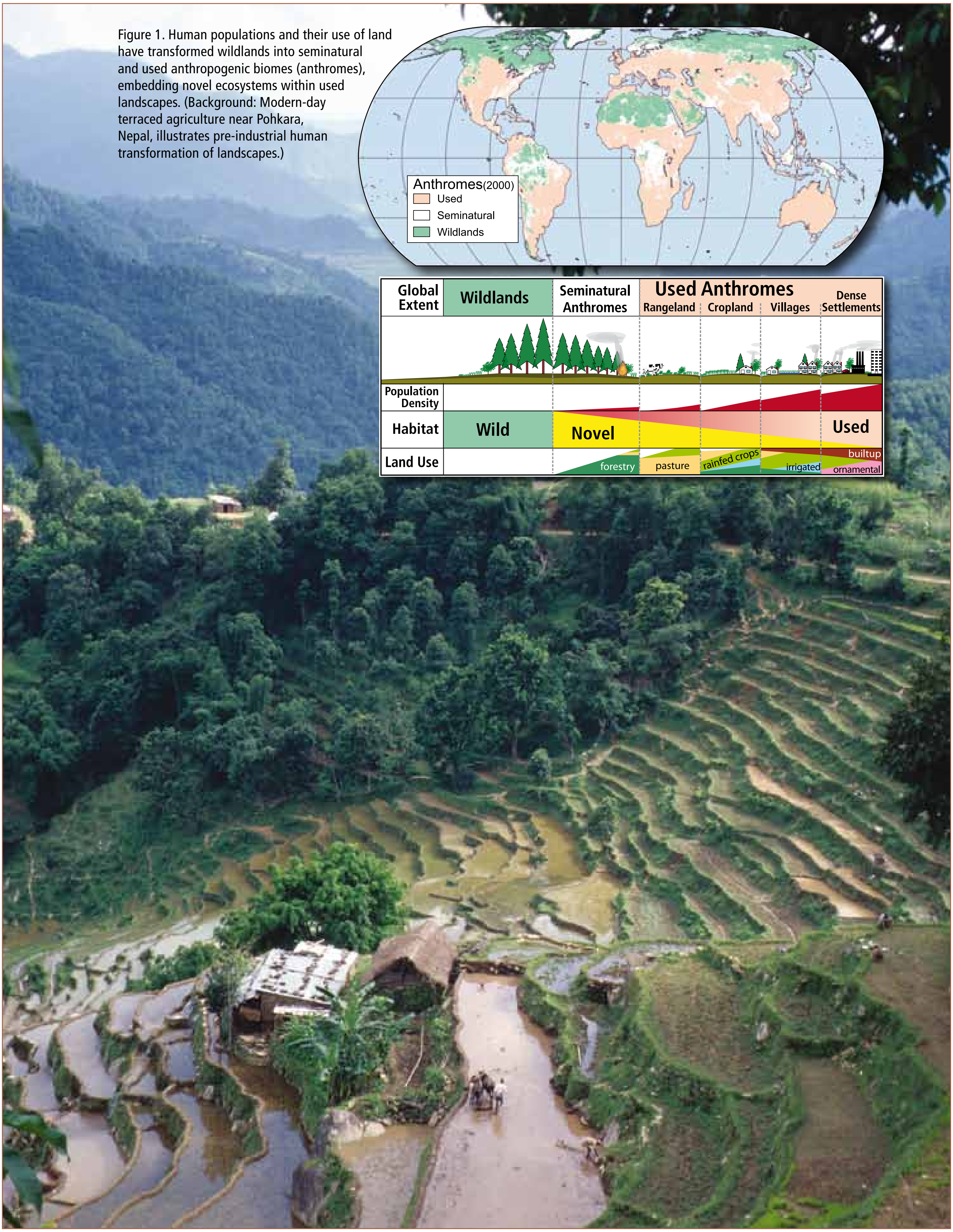


Figure 1. Human populations and their use of land have transformed wildlands into seminatural and used anthropogenic biomes (anthromes), embedding novel ecosystems within used landscapes. (Background: Modern-day terraced agriculture near Pohkara, Nepal, illustrates pre-industrial human transformation of landscapes.)

Erle C Ellis

response of human populations to demographic, social and economic pressures, leading to the adoption of increasingly productive land-use systems (Ellis *et al.* 2013). Put simply, humans don't make the effort to use land efficiently unless they must, for example, to feed a growing population with the same amount of land or to satisfy social or commercial demands. The least dense, least developed societies tend to use the most land per person.

Land use, long before the Holocene

Archaeological evidence in the form of plant and animal remains, charcoal, isotopic records and other legacies demonstrate that hunter-gatherers long ago engaged in pre- and proto-agricultural land-use intensification practices, to support larger populations on the same available land. At the same time, expanding populations also migrated to wilder regions.

Early humans broadened their diets by learning to eat more species once their preferred megafauna such as woolly mammoths became rare or extinct, often a result of hunting success by earlier generations. They set fire to parts of landscapes (a form of ecosystem engineering), burning vegetation to enhance hunting and foraging. They processed plant and animal foods to enhance their nutritional value, by developing cooking, grinding and other culinary tools that made many species, such as grasses, useful to humans for the first time. And they spread the plant foods they liked and managed populations of animals they hunted – and later would domesticate (Kirch 2005, Ellis *et al.* 2013).

Communities adopting agriculture in the early Holocene grew more rapidly than those of hunter-gatherers, ultimately replacing them across Earth's most productive lands. Intensification of land use continued: cultivation shifted from longer to shorter fallow periods, until eventually, continuous cropping became the norm, enhanced by the plow, irrigation, fertilizing with manure, and other increasingly productive technologies. Intensive agricultural systems gradually carpeted Earth's most productive lands, supporting densely populated villages and eventually supplying food to growing towns and cities.

As the demands of urban populations grew, ever-larger farming operations, trading systems and technological institutions developed to support them. By the 1950s, these demands, combined with political support for them, led to the high-yield "Green Revolution" land-use systems that are still developing today. This system is sustained by fossil fuels and other industrial inputs – and now by emerging technologies such as genetic engineering.

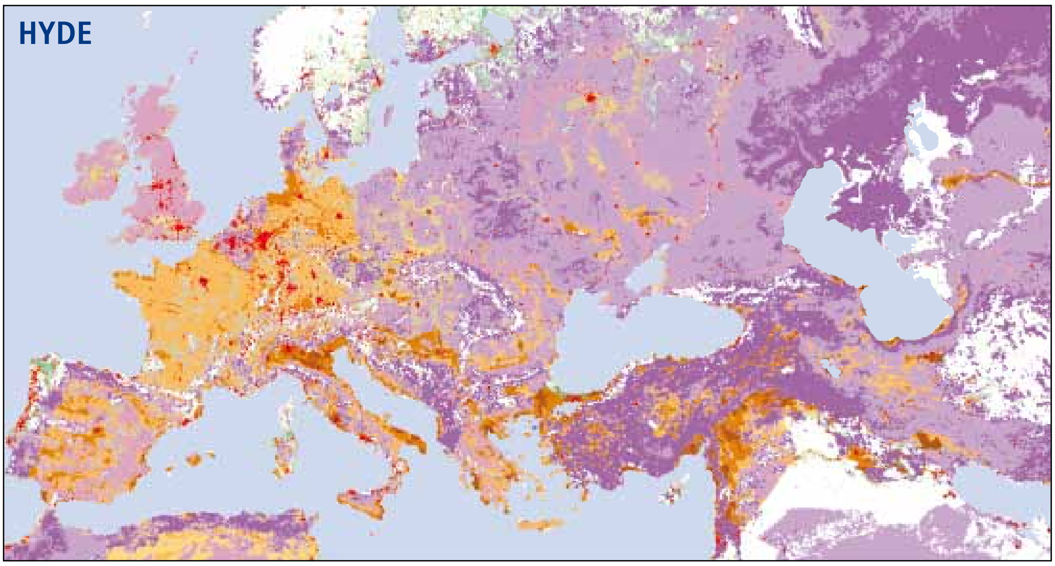


Figure 2. Land use in Europe more than 5000 years ago (3000 BCE) looks different in two models: the HYDE (left) shows less intensive human land use than the KK10 (right) model. Colour coding for the maps is below the map on the right.

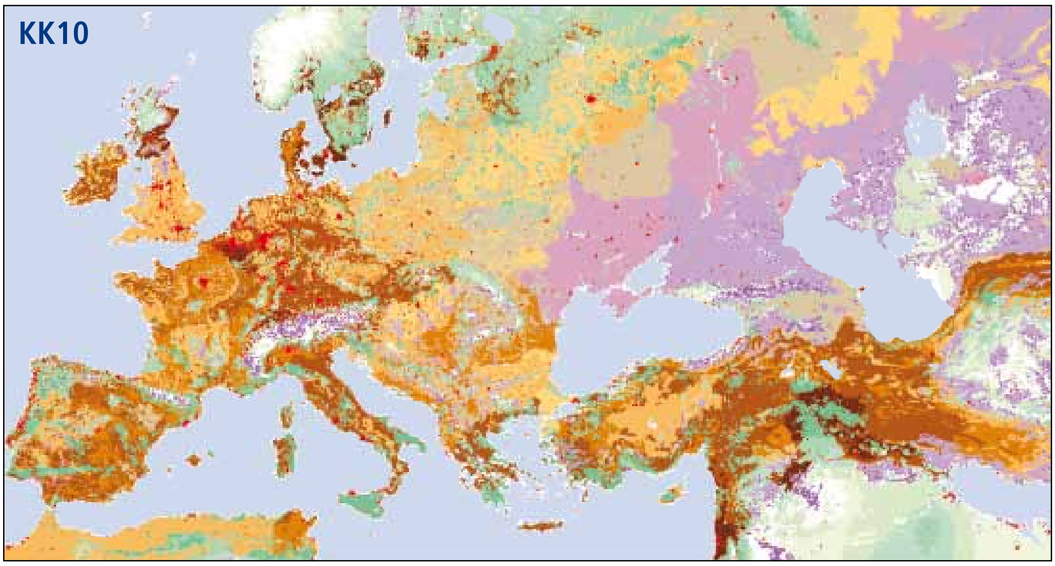
Societies tend to adopt more productive land-use systems as populations increase.

A tale of two planets

Societies tend to adopt more productive land-use systems as populations increase, but always within the shifting confines of their social, economic and environmental systems. Social and economic processes constrain land availability to potential users. Economic costs, governance systems and cultural values can limit adoption of more efficient technologies. Steep terrain, drought and other environmental constraints limit the potential productivity of land, which can also degrade with use over time, demanding greater inputs or even leading to land abandonment. Consequently, increasingly productive use of land is not a smooth and continuous process, but instead a complex succession of shifting land-use systems, with land sometimes backsliding into less productive uses. These changes subject populations to both surplus production and productivity crises.

Two new reconstructions of human populations and their use of land across the planet throughout the Holocene allow us to make the first quantitative assessment of the long-term dynamics of human land use (Figure 2; Ellis 2011, Ellis *et al.* 2013). Contemporary global patterns of land use and population come from modern census data and remote sensing imagery, which enable land use to be mapped from a bird's eye view. But land use prior to historical records (around 1700 in most regions) must be "backcasted" from contemporary patterns, using models of land use per person.

The results of these two reconstructions are so different



that they might as well come from two different planets (see Figure 2): a global land system model, HYDE (the History Database of the Global Environment dataset), shows that outside Europe's more developed regions, human use of land was insignificant before 1750. But a model nicknamed KK10 (the dataset from Kaplan & Krumhardt 2010) indicates that ancient people were using land at a global scale far earlier in the Holocene, with more than 20% of Europe and Asia already in use by 3000 Before Common Era (BCE), and large areas of Earth's land in recovery from higher levels of land use in earlier periods.

Why are the models so different? The first and most popular Holocene land-use reconstruction, HYDE, assumes that land use per person remained nearly constant over time: in other words, about the same amount of land was used to feed, clothe, house and otherwise satisfy the needs of each person, no matter the year. But KK10 takes an entirely different approach, estimating land use from population by means of empirically derived nonlinear relationships with population density based on data from palaeoecological and historical studies (Kaplan *et al*. 2011). The result is that low-density populations with high per-capita land use first expand to fill all usable land. Then they intensify their use of land, using less land per person as population densities increase over time.

So which model comes closer to the truth? At present, conclusively validating these global models of Holocene land use against empirical data across Earth's land is not yet possible. The requisite archaeological and palaeoecological data require compiling and standardising at global scale – a massive task. Nevertheless, by comparing existing models with what we know from archaeology, palaeoecology, geography and environmental history, it is clear that by incorporating adaptive changes in land use per capita over time, a more spatially detailed and plausible assessment of our planet's history is revealed, with a biosphere long ago affected by humans.

Learning from the ancestors

New models of land use across the many millennia of the Holocene suggest the central role of land-use intensification as a social process of global change in the Anthropocene. By enabling land productivity to increase over millennia, land-use intensification has allowed human populations to grow well beyond the potential of the unaltered biosphere to support them and helped sustain the emergence of large, technologically sophisticated, affluent and interconnected societies with the power to alter the course of Earth's history (Ellis *et al*. 2013). As we move deeper into the Anthropocene, strengthening our scientific understanding of the long-term social processes that sustain humanity has never been more important for the future stewardship of the planet.

New models of land use across the many millennia of the Holocene suggest [its] central role.

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Leaping over disciplinary shadows

Research increasingly crosses disciplinary boundaries and draws in outside stakeholders. **Karl-Heinz Erb, Veronika Gaube and Marina Fischer-Kowalski** report from two decades of experience in inter- and transdisciplinary research at the Institute of Social Ecology in Vienna, Austria. They advise on how to succeed in three not-so-easy steps.

Global environmental change confronts us with multifaceted problems. Getting good solutions to these challenges requires bridging the boundaries of scientific disciplines, in order to produce effective, useful information for policymakers and practitioners, as well as for stakeholders. Traditions of interdisciplinary work have emerged over the past few decades in many research contexts, such as under the umbrella of the Global Land Project, and can provide foundations and inspirations for new ways of working together.

We discuss here three preconditions for successful interdisciplinary and transdisciplinary research, gathered from our experiences at the Institute of Social Ecology in Vienna, Austria. Such programmes need to establish a joint focus on real-world problems; integrate not only the "flow" of the research process, but also the "stock", i.e. the scientific capital that research institutions have accumulated; and be able to draw upon changed reward systems.

A few definitions

In our work, we distinguish between interdisciplinary and transdisciplinary research. Interdisciplinary research draws on both the concepts and methods of various disciplines. Reaching across these boundaries is particularly challenging if disciplines have a long history of separation or follow different epistemological approaches. Such is the case for the disciplines on both sides of the "Great Divide" (Goldman and Schurman 2000, Snow 1959): natural sciences on the one hand, and social sciences and humanities on the other.

Transdisciplinary research not only bridges scientific traditions, but also draws in stakeholders from beyond the scientific realm: the actors who try to implement solutions politically and practically (Dressel *et al.* 2014).

Today, many scientific problems… cannot be adequately dealt with by isolated specialised disciplines.

Looking together

The key to successful interdisciplinary and transdisciplinary research is a joint focus on real-world problems and their solutions (Frodeman *et al.* 2010, Repko 2008). This kind of applied research contrasts with the analytical and insular traditions of scientific disciplines and communities (Gibbons *et al.* 1994).

Scientific specialisation was a huge achievement. Since the times of Humboldt, narrowed expertise and topical focus has been the silver bullet for scientific progress. But specialisation comes at a considerable cost – the cost of insularity – which interdisciplinary research attempts to overcome.

The barriers that specialisation has built up between fields are particularly obvious along the demarcation line between the two scientific "realms": the social and natural sciences. Each regards the other as simplistic, versus its own sphere, which is complex; this shared view of the other is a kind of remarkable agreement between these two worlds.

Each realm has also become rigid and sees itself in its own ways (see Figure 1). Sociological research, for example, restricts itself to the study of "social facts", following the seminal notion laid out by Émile Durkheim in 1895. Analogously, ecological research continues to predominantly focus on pristine, untouched parcels of nature even today, when those unspoiled patches are hard to find.

Today, many scientific problems, in particular those relating to global environmental change, cannot be adequately addressed by isolated specialised disciplines; each lacks the breadth necessary to capture the full range of real-world problems. Solutions require interdisciplinary teams.

Researchers in interdisciplinary teams find themselves in a hybrid role: within the team, they represent their disciplinary expertise, informing the science and

Interdisciplinary teamwork fosters reflections on the limits and confines of one's own discipline and is a prerequisite to approaching new scientific frontiers. Researchers from the Institute of Social Ecology meet to discuss strategies (pictured here).

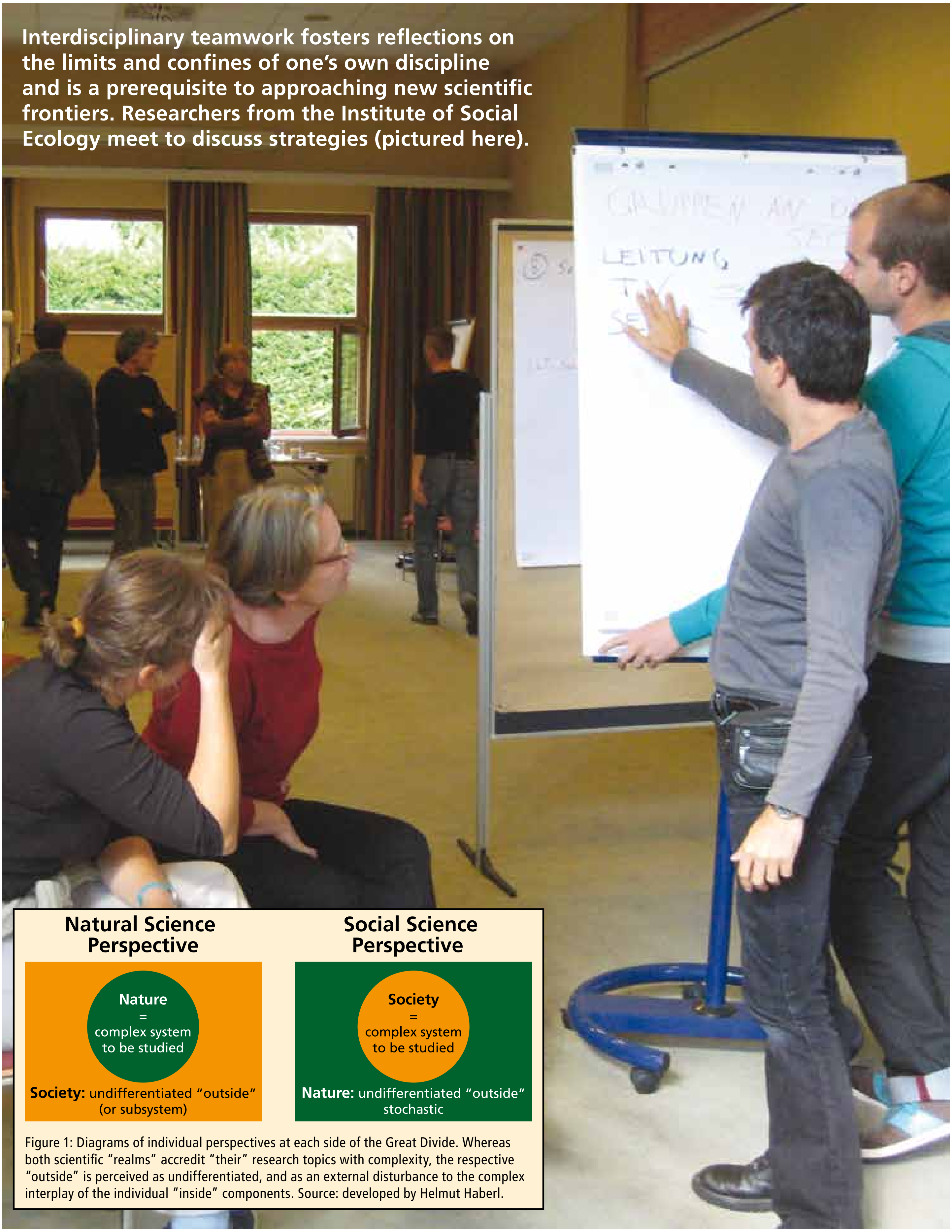

Figure 1: Diagrams of individual perspectives at each side of the Great Divide. Whereas both scientific "realms" accredit "their" research topics with complexity, the respective "outside" is perceived as undifferentiated, and as an external disturbance to the complex interplay of the individual "inside" components. Source: developed by Helmut Haberl.

Pilo Pichler

contributing to the success of a project. When interacting with other scientific communities, however, researchers have to represent interdisciplinary research questions and orientations.

Researchers working across the natural and social sciences are often asked, "What does socioeconomics tell us?" or "What do the natural sciences say?" These questions do not mean scientists have to be universal representatives of the entire social and natural science disciplines, but rather must serve as bridges between them. This double role is a challenge, of course, but it also allows individuals to gain expertise and to reflect on the limits and confines of their own disciplines, including its scientific jargon. Such open-minded thinking is a prerequisite to approaching new scientific frontiers.

A particularly powerful way to create strong connections between different disciplines while getting focused on real-world problems is to get a partner from the outside. Such an external partner can serve three functions, sometimes all at once: to "supply" the problem, benefit from proposed solutions, and be a motivating force. For example, a local air pollution board might seek preventative measures for problems triggered by intensifying land use in rural areas, which could be controlled with agricultural subsidies. The more critical, independent and yet closely involved such a partner is, the better the chances for interdisciplinarity; for transdisciplinarity, such a partner is indispensable.

The Global Land Project (GLP) explicitly addresses this orientation of research as one of its central approaches in exploring the role of human decision-making and actions regarding the terrestrial environment and the services ecosystems provide to society (GLP 2005). Research

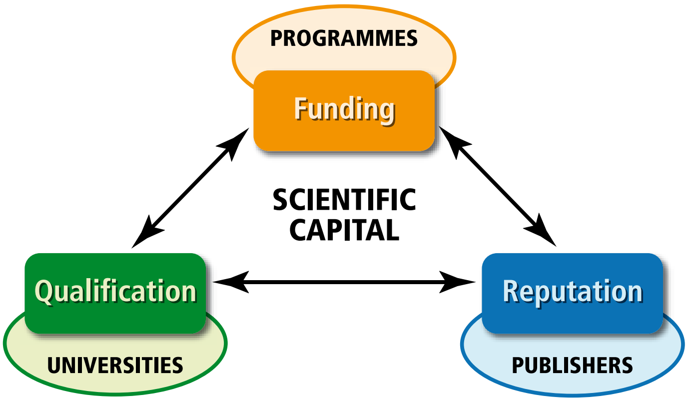

Figure 2: Funding, reputation and qualification are all provided by different institutions but have co-evolved over time, allowing research institutions to accumulate scientific capital.

An external partner can serve three functions, sometimes all at once.

projects endorsed under the GLP umbrella regularly involve non-academic experts and stakeholders in designing and evaluating policy strategies, for example, of sustainable land-use intensification, forest protection under climate change mitigation schemes such as REDD+ (an extension of the UN programme, Reducing Emissions from Deforestation and forest Degradation in developing countries, or REDD) or biodiversity conservation.

Scientific "capital"

The scientific system, including rewards and funding, evolved and adapted alongside the distinct scientific disciplines. In this process, research teams accumulate scientific capital that consists of databases, models and social networks, to address research questions. This capital accumulation typically involves huge long-term investments of time and money, and determines the research teams' potential to act in the future.

In the existing scientific landscape, such scientific capital is usually segregated by disciplines, or even more narrowly by institutionalised "micro-disciplines" (i.e. specific approaches shared by teams or research institutions). Sharing, changing or turning this capital to new schemes can be very costly and risky. Capital is usually hard to access for outsiders: for example, databases may lack metadata, models can be poorly documented, or social networks and connections may be informal. Thus, in terms of working time and social and financial investments, accumulated scientific capital constrains a research institution to its previous path, in order to keep doing research efficiently.

In our view, this so-called path dependency of scientific capital is the reason why "naïve" pleas for interdisciplinary cooperation made over the past few decades have not worked. If funders or framework programmes demand a quick jump to 'applications' of research results, then institutions fall into their existing routines of capital utilisation. This fallback position is not due to a lack of willingness to cooperate or work with experts from other disciplines, or even practitioners, but is inherently based on the internal logic of how institutions and their economics operate.

In order to overcome this logic, over the past few decades, the Institute of Social Ecology has shared and integrated scientific capital between its research teams, creating joint databases and expert networks across social, economic, ecological and technological realms. With the help of historical methods, these databases could be gradually extended for long time periods, according to conceptual system boundaries and consistent classifications that were repeatedly and thoroughly discussed. This process had to be piecemeal, based more on internal goodwill than on reliable funding to support the work.

Changing the reward system

Requests from funding programmes and agencies for interdisciplinary work will not suffice. The integration of scientific capital across institutional settings requires fundamental changes in scientific rewards. Three distinct but interdependent actors shape reward systems (Figure 2): funding agencies and research programmes, universities, and scientific publishers.

Funding agencies and research programmes provide financial assets, stringent reviews with well-defined quality criteria, and scholarly reputations. Universities also provide financial assets (though increasingly less over the past decades), in particular in the form of tenure, and offer defined routes of qualification (in the form of doctoral degrees, postdoctoral research positions, etc.), and so contribute to the build-up of reputation. Publishing houses organise other scholars in peer-review processes and so contribute to the formation of discipline-organised scientific communities (as do funding agencies' review committees). Successful publication, in particular in high-impact or high-profile journals, builds reputations for individuals, but also for research teams and institutions.

These three components of reward systems influence each other and lead to positive feedbacks (publication success leads to funding success leads to reputation leads to tenure) that reinforce the tendency of disciplines to be inwardly focused. Publications, as central currency for this interaction, have immense impact on the success rates for funding and other qualifications.

The successful implementation of inter- and transdisciplinary research requires the relaxation of the tight disciplinary bonds between universities, funders and publishers. Universities as well as funders can start to support cooperation between institutes, by adjusting quality-assurance systems such as peer review to the challenges of interdisciplinary research. Publishers as well as funding agencies need to recruit staffs of experts that are experienced in interdisciplinary research. On top of this, additional quality criteria beyond high-profile publications have to be defined. For example, successful stakeholder cooperation and knowledge transfer, which in our experience only rarely yields a high publication output, should be taken explicitly into account. Looking at the international research landscape, one might say that such changes are under way, but in a fashion that is still too disjointed.

Getting it together

Inter- and transdisciplinary research requires overcoming scientific disciplines' constructs and creating novel ways of organising the accumulation of scientific capital. Such change will only happen if supported by shifts in reward systems; that transformation will be challenging, as it means working against longstanding structures of scientific research. If a few preconditions are fulfilled, however, interdisciplinary research as well as co-design and production with non-academic experts can prosper. A credible provider of an outside perspective (for example, stakeholders) is extremely helpful for shifting the focus to innovative questions and research procedures.

For this to happen, an attitude of mutual respect between different members of interdisciplinary teams is fundamental. This approach includes renouncing scientific jargon, perhaps at the expense of communication efficiency, but with the advantage of openness to novel perspectives and insights. Most essential, though, is changing reward systems and establishing reliable partnerships, in particular between research and funding institutions. ▮

Transformation will be challenging, as it means working against longstanding structures of scientific research.

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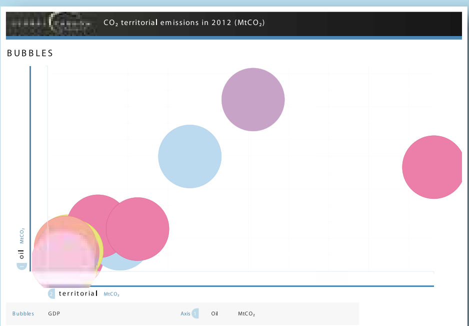
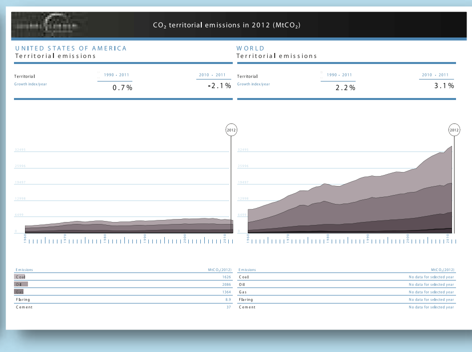
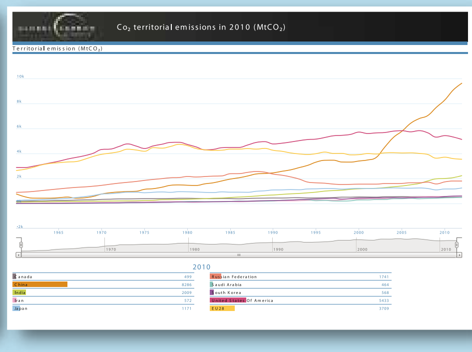
THE GLOBAL CARBON ATLAS







In November 2013, the Global Carbon Project launches the Global Carbon Atlas. The atlas is a comprehensive website with new visualization tools to generate maps and infographics, while providing easy access to the underlying data and sources.

- fossil fuel emissions by country
- carbon sinks in oceans, plants and soils
- carbon stored in forests, soils, permafrost, peatlands
- carbon emitted by deforestation and fires

The Global Carbon Atlas is for policymakers, businesses, NGOs, schools, journalists, scientists and the public.

www.globalcarbonatlas.org