Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Interactions of the carbon cycle, human activity, and the climate system: a research portfolio

Josep G Canadell[1], Philippe Ciais[2], Shobhakar Dhakal[3], Han Dolman[4], Pierre Friedlingstein[2,5], Kevin R Gurney[6,7], Alex Held[8], Robert B Jackson[9], Corinne Le Quéré[10,11], Elizabeth L Malone[12], Dennis S Ojima[13,14], Anand Patwardhan[15], Glen P Peters[16] and Michael R Raupach[1]

There has never been a greater need for delivering timely and policy-relevant information on the magnitude and evolution of the human-disturbed carbon cycle. In this paper, we present the main thematic areas of an ongoing global research agenda and prioritize future needs based on relevance for the evolution of the carbon–climate–human system. These include firstly, the delivery of routine updates of global and regional carbon budgets, including its attribution of variability and trends to underlying drivers; secondly, the assessment of the magnitude of the carbon–climate feedback; and thirdly, the exploration of pathways to climate stabilization and their uncertainties. Underpinning much of this research is the optimal deployment of a global carbon monitoring system that includes biophysical and socio-economic components.

Addresses
[1] Global Carbon Project, CSIRO Marine and Atmospheric Research, Canberra, ACT 2601, Australia
[2] Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, Gif sur Yvette, France
[3] Global Carbon Project, National Institute for Environmental Studies, Tsukuba, Japan
[4] Department of Hydrology and Geo-environmental Sciences, Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands
[5] QUEST/Department of Earth Sciences, University of Bristol, Bristol, United Kingdom
[6] Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN, USA
[7] Department of Agronomy, Purdue University, West Lafayette, IN, USA
[8] CSIRO Marine and Atmospheric Research, Canberra, ACT 2601, Australia
[9] Department of Biology and Nicholas School of the Environment, Duke University, Durham, NC, USA
[10] School of Environment Sciences, University of East Anglia, Norwich, United Kingdom
[11] British Antarctic Survey, Cambridge, United Kingdom
[12] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, Madison, USA
[13] The John H Heinz Center, Washington, DC, USA
[14] Natural Resource Ecology Laboratory, Colorado State University, CO, USA
[15] SJ Mehta School of Management, IIT, Powai, Mumbai, India
[16] Center for International Climate and Environmental Research, Oslo, Norway

Corresponding author: Canadell, Josep G (pep.canadell@csiro.au)

Current Opinion in Environmental Sustainability 2010, **2**:301–311

This review comes from a themed issue on Carbon and nitrogen cycles
Edited by Josep G Canadell

Received 11 May 2010; Accepted 23 August 2010

1877-3435/$ – see front matter

DOI 10.1016/j.cosust.2010.08.003

Introduction

The core goal of the carbon cycle research community in responding to the climate change challenge is to understand the role of the natural and managed carbon cycle in the dynamics of the climate system. That requires quantifying the effect of human activities on the carbon cycle [1]; determining the response of natural systems to these disturbances; projecting future behavior of carbon pools and fluxes; and exploring pathways to atmospheric stabilization through the management of the carbon–climate–human system. A diverse set of national and international carbon research agendas consistent with these objectives has been developed over the last decade. In particular, the Global Carbon Project was established by the Earth System Science Partnership 10 years ago with a research agenda that reflects the goals outlined above and with the mandate to develop a globally coordinated research strategy for its implementation [2,3•].

However, the rapidly evolving scientific and policy landscapes call for a continue reassessment of research priorities and ways the scientific information is produced and delivered to key users of carbon information.

New emerging knowledge includes firstly, the possibility of a decline in the efficiency of natural carbon dioxide (CO_2) sinks, which, if confirmed and persistent, will lead to faster atmospheric CO_2 accumulation [4••,5•,6••,7]; secondly, a wider recognition of the existence of vast carbon reservoirs on land and oceans vulnerable to destabilization, and potentially leading to enhanced carbon emissions from natural systems [8–10,11•,12]; thirdly, the emergence of ocean acidification as a major ocean-wide impact from excess anthropogenic CO_2 [13•,14]; and fourthly, the high sensitivity of the methane cycle to climatic factors and its future dynamics [15,16].

New emerging policy issues include firstly, the increased requirements for Monitoring, Reporting and Verification (MRV) to support climate-policy development and implementation; secondly, the conflicting policy demands for carbon-based products related to food security, energy security, and biodiversity conservation; and thirdly, the wide recognition of possible unintended consequences of large-scale manipulation of carbon–climate interactions with the goal of mitigating climate change.

In this paper, we outline continued and emerging research areas, with an emphasis on those with the greatest need for an interdisciplinary, global scientific effort. We structured the paper in four sections. The first three sections cover the main research domains consistent with the goals of the broader research agenda described above: *diagnostics of the carbon cycle* — the observation and quantification of the human disturbance on the carbon cycle; *vulnerabilities of the carbon cycle* — understanding the processes driving carbon fluxes and their role in the present and future climate system; and *low carbon pathways* — identifying key leverage points for climate mitigation and building resilience in the carbon–climate–human system. All three research domains are closely interconnected and need to be addressed simultaneously; however, key diagnostics of the carbon cycle are required to place the relevance in space and time of driving processes, and the exploration of future trends; low carbon pathways need to build inevitably upon the knowledge of the magnitude of the fluxes and their driving processes. Within each section, there are a number of broad research questions representing areas of high relevance for which major research and observation gaps exist. The final section provides a prioritization of the agenda with an initial set of engagements with other international bodies, policy development, and outreach to the broader society.

Diagnostics of the carbon cycle

Quantification of carbon sources and sinks, their spatial distribution and evolution over time remain a critical area of research. Two key goals justify this investment.

First, the magnitude and dynamics of the human disturbance on carbon flows and pools must be quantitatively understood and assessed over time in order to determine levels of mitigation and their uncertainty ranges required to achieve temperature targets. Climate policies depend on this type of information to help design efficient mitigation policies for a given temperature target. This is an area of active research, where integrated global carbon observations are used to constrain regional fluxes and pools. At present, uncertainty of national or continental budgets is on the order of 50% at the best, and around 30% for global natural fluxes [4••,6••,17•,18,19••,20••].

Second, there is an increasing need for capacity to Monitor, Report and Verify (MRV) climate mitigation activities resulting from global treaties, national and sub-national policies. Key to this requirement is the provision of a broader set of observations and model systems capable of assessing the adequacy of, and compliance with climate policies. Clearly, the emergence of carbon markets and the ultimate growth of a global carbon economy can only be built upon an independent, robust, transparent, and scientifically based MRV capability. This will require appropriate institutions to assist this high-level policy-based science such as the establishment of an agency or consortium of agencies to assume and implement this new mandate [21].

Although the focus of this agenda is on carbon, largely CO_2 and CH_4, future analyses need to include other carbon and non-carbon greenhouse gases such black carbon and nitrous oxides (N_2O). The initial choice of CO_2 and CH_4 is because they are the two largest contributors of anthropogenic greenhouse gases (GHG)-driven climate forcing, together accounting for 83% in 2008. Carbon dioxide alone is responsible for 80% of the current growth in climate forcing due to all major GHG [22,23].

What is the evolution of the global anthropogenic CO_2 budget?

Establishing and attempting to close the global carbon budget (adding and subtracting all major sources and sinks should equal zero) provides a global consistency check on how confident we are in assessing the magnitude of the human disturbance and attributing it to its component fluxes.

Because the human disturbance occurs on top of an active natural carbon cycle, which in part hides the human disturbance, the requirements for accuracy are high. Thus, a key research area is to reduce uncertainty on the global budget to levels adequate for process attribution and assessment of GHG impacts of climate mitigation. This will be done through improved observations and models for each of the component fluxes including further constraining the flux from land use change, currently the most uncertain flux of the global carbon balance [4••,6••]. Reducing errors in the quantification of fossil fuel emissions also requires increasing attention to leading regions undergoing rapid economic growth with detected errors of as much as 20% [25].

Two key observationally based diagnostics provide important information on the evolution of the carbon budget: the trend in the airborne fraction — the fraction of emissions from human activity that remains in the atmosphere [4••,6••,7,26] and the carbon intensity of the economy — the amount of carbon emitted to produce one dollar of wealth [27•]. In addition, testing short-term projections with actual observations provides continuous verification of initial assumptions. Recently, this type of comparison revealed that the growth rate of fossil fuel CO_2 emissions over the last decade was above the average emission from all IPCC emission scenario families [1,27•].

What is the evolution of the global CH_4 budget?

Methane atmospheric concentration has been relatively stable over the last two decades but a recent spike in concentration suggests that methane emissions are highly sensitive to climate fluctuations, and thus possibly to climate change, and wetland distribution.

Given the diversity of CH_4 sources and the sensitivity of CH_4 removal on the complex nature of atmospheric hydroxyl radical (OH) chemistry, there is a need to understand better the spatial distribution and chemistry of emissions that affect OH concentrations and how they relate to human activities and natural processes [28].

Key goals in understanding the CH_4 budget are firstly, to improve the capacity to analyze and attribute changes in atmospheric CH_4, and secondly, to better understand the causes of variability of methane sources including both natural (e.g. from Northern and tropical wetlands) and human (e.g. livestock, rice paddies, and fossil fuel). An outcome of this effort should be the capacity to establish an annual or biennial update of the global methane budget.

Source quantification and atmospheric observation of atmospheric CH_4 at higher space and time resolution will provide the ability to detect emissions hot spots such as new methane sources from wetlands, industry, fires or permafrost hydrates.

What are the regional contributions to the global carbon balance?

The development of carbon budgets and their dynamics over time at the regional and national scales stems from the need for higher spatial resolution that is possible with current global approaches. Regional budgets can be constructed by utilizing global models and data products along with higher density observations, models and process information unique to the regions. Initial estimates of regional contributions to the global biological terrestrial net carbon sink are, on average, 0.23 PgC for China [29], 0.27 PgC for continental Europe [20••], 0.5 PgC for North America [19••], and a net sink of 1.7 PgC for the entire Northern Hemisphere extra-tropical region [20••]. Some of these estimates have errors as big as 50%.

A key potential application of regional budgets is to support, monitor and verify regional emissions and the outcomes of mitigation activities, further constraining the already existing sectoral GHG emission inventories.

Well-defined methodologies to establish regional budgets and their uncertainties will improve the intercomparability among regions, while allowing using regional fluxes to constrain the global budget and vice versa. The reconciliation of top-down atmospheric inversions with bottom-up estimates constitutes an essential process for building confidence in the regional estimates. Improved diagnosis of regional budgets will also favor the benchmarking of coupled carbon–climate models by using observations, and help reduce error in future projections of the carbon cycle. With the aid of models, improved regional budgets in areas with dense observations will help to attribute fluxes to underlying processes and drivers.

Enhancing observations and analyses in a globally coordinated strategy

All the objectives above cannot be achieved without an enhanced global carbon observing system to fill current gaps in knowledge on the carbon cycle [30], and as established by the Group on Earth Observations [31]. Such a system needs to embrace both global and regional components, bottom-up and top-down observations and modeling, and a capacity to report and analyze results in a timely fashion. It needs to include observations, their uncertainties and quantification of both biophysical variables and those characterizing human activities and underlying drivers. While progress is being made in some regions of the world, critically important regions for the global carbon balance, such as the tropics and high-latitude regions with carbon-rich soils, lack fundamental observations. This has led to large uncertainties in present estimates of carbon pool sizes and the vulnerability of those pools to anthropogenic disturbance. Deployment of observation systems to track the extent of ocean acidification is also needed.

A research area for further development relates to multiple constraint approaches, as new observational platforms and multiple-model ensembles become more readily available. Particularly important is the advent of the continuous GHG measurements from satellites. Continued network design activities are needed to identify sensor and validation network characteristics to meet observational goals. In the international effort to reconcile top-down and bottom-up estimates of fluxes, processes and the overall carbon balance, the application of formal model-data assimilation techniques capable of dealing with multiple data streams (well established in weather and hydrological forecasting) remains a major research area [32,33].

Vulnerabilities of the carbon cycle

A significant contributor to uncertainty on the magnitude and rate of future climate change is lack of understanding of the feedbacks between anthropogenic emissions, the carbon cycle and the climate system. As much as 40% of the uncertainty in the model spread of climate change projections for the 21st century might be due to variable characterization of the dynamics of the carbon cycle [34]. Further uncertainty comes from pools and processes not included in the current generation of earth system models, such as decomposition of thawing organic carbon [10], vulnerability of methane hydrates to warming and resource extraction [11•], interactions between climate change, stratospheric ozone depletion and the strength of ocean carbon sinks [35], and synergistic effects of drought and deforestation on land emissions [36].

Although carbon–climate feedbacks can enhance either sources or sinks of CO_2, a subset of these vulnerabilities currently included in earth system models consistently show increased source emissions. This represents a highly unconstraint positive feedback to climate change between 20 and 200 ppm of additional CO_2 by the end of this century [37••].

Additional vulnerabilities on carbon pools emerged from complex interactions among human activities and climate variability and change. Examples are food policies, peat drainage, drought and fires in parts of Southeast Asia and Russia, or commodity prices, forest degradation and fire in tropical regions.

How big and vulnerable are the Earth's carbon reservoirs?

An important limitation to characterize the magnitude of carbon–climate feedbacks is a better assessment of the size, spatial distribution, uncertainty, and likelihood of disturbance of carbon pools, which potentially can lead to new or enhanced emission sources. Major biospheric and fossil carbon reservoirs include permafrost, peat, mineral soils, biomass, oil, gas, coal, and methane hydrates.

An additional need is to provide a consistent measure of uncertainty that can be appropriately propagated in vulnerability analyses and in the projections of carbon–climate feedbacks.

Are there irreversible carbon thresholds?

A key development in process research, modeling, and observations is the ability to identify non-linearities, thresholds and irreversible processes. Examples are the potential self-sustained thawing of permafrost triggered by human-induced warming [38••], the rapid increase in fire occurrence and vegetation replacement due to the interactions between reduced rainfall and tropical deforestation under future climates [8], peatland drainage and associated fires [39••,40], ocean acidification on ocean productivity [11•,12], and the long-term effects of major global financial crises and oil price shocks on the carbon intensity of the economy and underlying drivers. The ability to assess risks of possible thresholds is essential for policy development and development of mitigation targets which include conservation of carbon sinks and pools.

What is the magnitude of the carbon–climate feedback?

Although the magnitude of individual carbon–climate feedbacks might not seem significant next to the large fluxes from the combustion of fossil fuels, the combined effects of multiple carbon vulnerabilities can be significant [37••]. These vulnerabilities include firstly, changes in the strength of carbon sinks; secondly, increased carbon emissions from the destabilization of carbon pools by climate change and human activity; thirdly, other vulnerabilities associated with changes in non-CO_2 radiative forcing and their human and biophysical underlying drivers; and fourthly, uncertainty in climate sensitivity.

Land and ocean biogeochemical models with appropriate development and validation of new critical processes will provide measurements of the magnitude of individual vulnerabilities. The development of simple analytical tools will allow exploration of the magnitude and range of multiple vulnerabilities and their interactions. Complex earth system models of the family of C4MIP (Climate Carbon Cycle Coupled Model Inter-comparison), with significant advances in complexity and processes representation, will ultimately provide the magnitude and timing of the combined vulnerabilities in the biophysical context. Some of the still missing or poorly constrained processes include the role of nutrient availability, disturbances, and land management [41,42]. Model improvements will enable to address complex questions as the role of oceans to degassing CO_2 to the atmosphere as the atmospheric concentrations of CO_2 begin to decline in the future, or the interactions between the CO_2 fertilization effect on productivity and nutrient limitation. The dynamics of the natural climate–carbon system as recorded in ice cores will also provide constraints on the magnitude of the climate–carbon cycle feedback [43].

What are emerging human–carbon interactions of most significance?

Societal and individual decisions leading to GHGs emissions and land use changes (and thus to changes in carbon sources and sinks) need to be characterized along with the responses of the carbon cycle.

Quantification of key drivers of fossil fuel emissions and land use emissions are required to identify leverage points for intervention including the carbon intensity of the economy, population growth, income growth, lifestyles and international market forces which impact domestic policies. In addition, most past studies have focused on drivers that start at the point of production and there is increased need for studies that focus on consumption and lifestyles as a key emission driver [44]. At the regional level, more attention is needed on the international trade of goods and services which allows increased consumption with production and emissions occurring elsewhere [44,45••,46,47].

Rapidly emerging economies are locking into high emission pathways calling for the need to assess development models that allow countries to reach a high-level of life satisfaction without replicating the high per capita emissions in today's developed countries. Likewise, carbon pricing will affect the rate of development and the adaptation of energy technologies by countries. These include considerations of technological advances such as carbon capture and storage and global implementation of bioenergy systems.

The coupling of carbon cycle and climate models with socio-economic models provides a venue to move toward whole system assessment of vulnerabilities with human and biophysical components as interactive drivers of change. Simpler conceptual models will enable to explore the consequences of multiple interactions, including the necessary elements for resilient systems. Coupling with integrated assessment models (IAMs) will cross-validate models and provide additional insights on the interplay between human decisions and changes in carbon stocks and flows. These would include choices in carbon mitigation pathways, low carbon development strategies, major policies of global significance (e.g. biofuel targets), rapid economic growth of emerging nations, financial crisis and oil price shocks, technological developments (e.g. extraction of methane hydrates or deployment of massive bioenergy systems), and the implementation of new carbon markets. Integration needs to include all positive and negative feedbacks.

What is the role of biodiversity for the resilience of carbon pools and sinks?

Through genetic information, and species and ecosystem interactions, biodiversity is linked to many ecosystem and earth system functions. A number of relationships have been established among functional biodiversity, resilience of functions and the impacts of loss and gain of species. However, the link between biodiversity, and the size and stability of carbon pools and fluxes over time is still elusive, and thus slowing down the design of more resilient carbon sinks while protecting their carbon pools and biodiversity [48].

The relevance of these interconnections is becoming rapidly apparent as impacts of ocean acidification on marine species are better understood, and discussions are underway for large-scale sink enhancement projects, and more in general, large-scale manipulations of land, oceans and atmosphere that will affect both biodiversity and carbon pools and fluxes.

Low carbon pathways

What is the global mitigation potential of land-based options?

Three interconnected agendas are likely to drive major land transformation during this century: climate change mitigation, food security, and energy security. All three lead to higher demands for land and altered land uses. The ensuing changes will bring not only opportunities for development but also possible unintended negative consequences on the environment and downstream socio-economic implications.

Because the interplay of these three agendas will be unique for different regions of the world, both global and regional approaches are required to assess the mitigation potential that can be achieved with sustainable development principles and under different socio-economic scenarios (e.g. with or without the existence of international carbon markets). Multiple and complementary approaches include the establishment of opportunity costs (an economic approach), the establishment of resilient systems and pathways (a systems approach), and assessing land availability, land quality and optimal usage (a resource assessment approach). Such assessments will enable researchers to explore scenarios, resolve trade-offs, ensure sustainable principles, and align win–win activities, including support for combined mitigation and adaptation efforts. Thus, an integrated assessment approach is fundamental to establish a portfolio of mitigation options [49]. The results will also inform which strategies and combinations work best in a given region. A key uncertainty is the carbon balance of global agriculture, both intensive (industrial) and non-intensive, and the national and international policies that can encourage management for carbon sequestration. Research and development on governance to deal with complex interlinked policies that address climate change, food security, and energy security will be critical for successful policy outcomes.

How climate protective are land-based mitigation options?

Changes in land use and land cover that sequester carbon in plant biomass and soils can be used to reduce net carbon emissions from human activities. However, land-based mitigation affects climate through more ways than carbon sequestration alone. The emissions of methane, nitrous oxide, and other trace gases differ substantially with land use and management strategies, including irrigation and fertilizer use [50]. Additionally, changes in land use and land cover lead to changes in surface reflectance (albedo), surface energy balances, which affect climate and may even dominate over biogeochemical factors [51]. For instance, forestry projects typically darken the land surface compared to pastures, agricultural lands, and snow-covered surfaces, increasing the absorption of sunlight. In contrast, crops tend to brighten the land surface, cooling a system if other terms of the energy balance remain the same. Other important biophysical changes alter the amount of water that evaporates or transpires from plants and the soil, the roughness or unevenness of the plant canopy, and ultimately the extent of convective clouds and rainfall. Thus, the net climate benefits of land use and cover changes must be assessed as the balance between GHG fluxes and biophysical properties of the land surface.

The potential climate benefits of reforestation in the tropics are likely to be large because biogeochemical benefits are further enhanced by positive biophysical changes such as water recycling and cloud formation, reflecting additional sunlight. This positive feedback adds to the justification for efforts such as Reduced Emissions from Deforestation and Degradation (REDD) in the tropics [52]. In contrast, climate models suggest that large reforestation programs in snow-dominated regions may have limited climate benefits because of the substitution of bright snow in winter for dark forest canopies if evergreen tree species are used [53,54]. Large uncertainties exist on the direction and magnitude of the biophysical effects in temperate and arid regions.

Assessing the net radiative effects of large-scale land transformation can best be advanced with a combination of regional to global land-surface models combined with more extensive remote-sensing and field observations. Fully coupled global and regional models along with biogeochemical models are needed to assess the relative contribution of biogeochemical and biophysical effects [55]. Understanding where both carbon storage and biophysics align to reduce net radiative forcing and where they might partially cancel each other out will inform the design and spatial distribution of large-scale mitigation interventions. New scientific information can be used to develop a set of spatially explicit rules on where the highest and least climate benefits can be achieved [56].

What are the carbon cycle consequences of geoengineering the climate system?

Without advocating the use of geoengineering intervention strategies, we recognize that the scientific community needs to provide scientific input into the debate on geoengineering proposals. Important scientific gaps include the mitigation potential of geoengineering and the potential for unintended consequences to other components of the interconnected earth system. This knowledge, with an appropriate quantification of the uncertainties, needs to inform discussions with technical and policy bodies, in addition to educating the general public on both the potential benefits and risks posed by these proposed climate solutions.

The current diverse portfolio of geoengineering options falls mainly in two categories: firstly, solar radiation management such as spraying aerosols in the upper atmosphere or brightening clouds with sea salt, and secondly, CO_2 removal from the atmosphere by biological or chemical means. The options with implications for the global and regional net carbon balances are of most interest. Issues include: firstly, the impact of stratospheric aerosol injection on the land and ocean carbon reservoirs, in particular not only through the impact of increase of diffuse light on primary production, but also through indirect pathways such as possible changes in stratospheric ozone and surface winds; secondly, the availability of soil nutrients such as nitrogen and phosphorus to meet the demands of sustained productivity of large-scale afforestation projects; and thirdly, the effects of iron fertilization on other trophic chains and biodiversity in general, including fisheries. An integrated perspective is needed for each geoengineering strategy that assesses GHG fluxes and biophysical properties on land and in the oceans, as well as unintended environmental co-effects. This need unifies carbon-cycle research across a suite of mitigation options inside and outside geoengineering.

How much urban mitigation can contribute to emission reductions?

Over half of the world's population lives in urban environments and this fraction is expected to increase. This fact highlights the importance of urban environments as a focus for mitigation opportunities. There is an important research agenda in understanding and quantifying how changes to existing urban infrastructure, lifestyles, and governance institutions can drive reduced GHG emissions. Options include new and efficient technologies in the production and consumption of stationary and transport energy, enhancements to the efficiency of older technologies, improved urban and building design, and better carbon governance. Changes in the behavior of urban dwellers will also be of increasing importance [57] — for example, choices in transport, the 'walkability' of urban spaces, and the use of household and communities gardens for food and aesthetics. A key challenge is that as urban density increases, a larger share of production and emissions will occur outside of the city limits creating accounting and burden-shifting problems [58]. Hundreds of millions of people will likely move into urban areas over the next decades providing an unprecedented opportunity to develop more efficient, better designed, and better governed urban regions.

There are a number of key research issues in the evolving urban carbon agenda. First, we need a clear understanding of the carbon footprints of urban regions including an assessment of the implications of considering different urban system boundaries, a key element of uncertainty when determining emissions responsibility of urban regions.

Second, it is important to determine what portion of urban emissions are amenable to management by municipal governments and other urban institutions; this will ultimately provide a global estimate of the potential direct mitigation benefit from better urban design and management. For example, control over the provision of energy to some urban regions is regulated at the provincial, state, or national scale. Cities can still play critical roles but more effectively as facilitators rather than actors [59].

Third, the most successful solutions for mitigating GHG emissions will be those that exploit co-benefits, such as on water use, improved air quality, better transport systems, and greener cities [60].

Fourth, comparative city studies can reveal less carbon-intensive urban development pathways and opportunities for retrofitting existing or developing designs. An examination of cities with current mitigation and adaptation plans can provide a basis to quantify co-benefits in different development paths.

Fifth, mitigation must also be examined in the light of equity issues, recognizing the disproportionate impacts of climate change and costs of mitigation activities on poor and otherwise vulnerable people.

Finally, an assessment of urban areas allows focus on lifestyles and consumption patterns as emission drivers. Studies find that the level of income is the dominant determinant of household environmental impacts. Further research is needed on ways to reach a high-level of life satisfaction at reduced per capita emissions in developed counties and to facilitate a low carbon pathway in developing countries.

What are the requirements to achieve atmospheric CO_2 stabilization and how to share the mitigation efforts?

The selection of a global warming target and how to share the mitigation burden among nations is largely a political decision based on the science of climate change, economics and ethical considerations. Among the science that is required to inform the policy process, there is a great deal of fundamental carbon cycle information which we divide in five categories.

First, to achieve atmospheric CO_2 stabilization requires an understanding of both the evolution of the human disturbance of the carbon cycle (i.e. largely CO_2 emissions from fossil fuels and land use change), and the evolution of the strength of the natural sources and sinks of carbon (on land and oceans). In particular, the vulnerability of the carbon cycle to the human disturbance has to be factored in the mitigation pathways for stabilization.

Second, relating emissions pathways to atmospheric concentrations or global temperature is a complex process requiring input from many research fields [61]. The probabilistic relationship between cumulative anthropogenic CO_2 emissions and peak global temperature above preindustrial levels is a new emerging approach [62•,63]. A related issue is to determine what are the maximum levels of residual emissions allowed, if any, after climate stabilization has been achieved.

Climate stabilization is not necessarily the same as the level of stabilization required to maintain healthy ocean ecosystems, as progressing acidification may have strong effects on the stability of ocean life, long before temperature stabilization levels are achieved. Thus, this requires a coordinated but additional research effort.

Third, quantification of past, current, and likely future carbon emissions and sinks of different regions and nations will inform the debate on the biophysical responsibility for having produced climate change. Increases in gross domestic product over time are currently a key driver for regional emissions [27•], and given current disparities, reaching equity in life satisfaction across regions without equal emissions is a key challenge. An emergent issue at the regional level is the rapid increase in flows of embedded carbon in traded products which allows countries to increase levels of consumption without associated increases in emissions [44,45••]. On the basis of the consumption accounting, up to 50% of emissions from some of Western European countries are produced outside of the country [45••], while 50% of the emissions growth in China over the last few years is due to the manufacturing of goods for export [64].

Fourth, to analyze the effects of carbon pricing effects on energy and mitigation costs and technological pathways. A related research development in this area is the allocation of emissions from fossil fuel and land use change to human drivers, with country comparisons of similar and different development pathways. Strategic analyses on key emerging countries/regions (e.g. China, India, Brazil, Russia Federation, South Africa) will further help to understand the causes and likely evolution of emissions from human activity, and to focus in developing the capacity in these regions to develop low carbon pathways.

Research priorities

We have presented a broad yet coherent research agenda to quantify and understand the carbon cycle and reduce uncertainty on its future evolution. The research and synthesis presented build upon observations, experiments, and synthesis efforts coming from disciplinary and multi-disciplinary efforts.

In this section, we outline an initial set of research priorities emerging from today's state of knowledge of the carbon cycle and its significance for the evolution of the earth system. New knowledge and the future evolution of anthropogenic forcing will undoubtedly lead to new assessments of priorities. Emphasis is also placed on efforts that require a higher level of integration and international cooperation to achieve its final objectives. These form a linked set rather than a list ordered by significance.

1. *Optimal deployment of a Global Carbon Monitoring System*. The design and implementation of an optimal global carbon observation system underpins much of the carbon cycle research. This requires a global network of countries and key agencies as it is envisioned by the Group on Earth Observations (GEO). This system is needed to monitor changing global and regional carbon budgets in consistent ways, including both trends and variations (see Priority 2), and to provide an enhanced capacity to Monitor, Report and Verify (MRV) the outcomes of climate policies. The optimal system will use the best available knowledge of the carbon cycle to implement ground-based observations and satellites in a way that uncertainties will be reduced in a cost-effective way, avoiding duplications, gaps, minimizing biases and other sources of uncertainties. This will be a system of systems combining global perennial components (e.g. GHG retrievals from satellites, global sampling networks, earth system models) with regional components capable of providing sufficient spatial resolution to detect, quantify and attribute changes of the natural and anthropogenic carbon fluxes and pools. New observation platforms and extensions to current ones are necessary, including a denser network of atmospheric sampling stations and more regular and extensive soil and vegetation carbon inventories. Improved model-data assimilation approaches are required to benefit fully from the multiple streams of bottom-up and top-down data available. The models themselves require more accurate representation of atmospheric transport, more realistic ecosystem and ocean carbon processes, and adequate model resolution to minimize sampling and representation errors. At present, model uncertainty is large (as quantified from intercomparisons) limiting the accuracy of the carbon cycle diagnostic. Models must improve and be tested against observations, and ultimately, improvements will largely depend on new high quality data to enable future reanalysis of trends and variability. A comprehensive monitoring system will undoubtedly need to include components that relate to socio-economic drivers of carbon fluxes such as energy consumption, GDP, and population distribution.
2. *Delivery of routine updates of global and regional carbon budgets, and attribution of variability and trends to underlying drivers*. The magnitude of the human disturbance of the carbon cycle is a key diagnostic of the evolution of climate change and the effectiveness of climate policies. One overarching research requirement and one operational requirement are needed for carbon budget data to be useful. First, uncertainty of all carbon fluxes must come down significantly. Currently, some flux uncertainties (for instances on land use change) might be as high as 50%. Second, the timely processing and delivery of carbon budgets require an operationalization of data retrieval, modeling and analyses, and therefore a transition from the current research-based funding arrangement to one of the climate change services. The attribution of observed variability and trends to natural and anthropogenic processes requires advanced analysis of the regional contribution (including urban components) in conjunction with other biophysical and socio-economic information. This priority will be greatly aided by the Global Carbon Observation System outlined in Priority 1, but much can be done before that system is fully deployed.
3. *Assessment of the magnitude of the carbon–climate feedback*. Sources of positive and negative feedbacks should be investigated at different time scales. Land and ocean processes with the potential for large influences in carbon fluxes need to be better constrained and incorporated into to the carbon cycle component of Earth system models. This includes firstly, constraining the CO_2 fertilization effect on ecosystem productivity and its interactions with water and nutrient availability, including possible shifts in nutrient limitation; secondly, the role of disturbances and land management; thirdly, the role of ocean acidification on ocean CO_2 fluxes; and fourthly, a much improved assessment of the magnitude and vulnerability of carbon pools to climate change and human intervention, particularly for organic soils such as those in permafrost regions and peatlands.
4. *Exploration of pathways to climate stabilization and uncertainties*. A full integrative approach is required to address the realistic potential and effectiveness of carbon mitigation options. This includes allowing competitive interactions among multiple mitigation strategies and addressing both biogeochemical and biophysical aspects of the resulting changes in radiative forcing. Particular consideration needs to be given to the production of bioenergy as a potentially important long-term carbon mitigation option, in addition to conservation of current carbon pools (e.g. Reduced Emissions from Deforestation and Degradation, REDD). Ultimately, this type of information must deliver plausible biogeophysical pathways to achieve atmospheric GHG and temperature targets such as the 2°C target established by the United Nations Copenhagen Accord in 2009. Analysis of carbon flows of embedded carbon in products and services at multiple scales (e.g. cities, national) provide a strong link between the physical carbon cycle and the policies and human activity that drives them.

The next two points are not research priorities but key components of the process, extension and delivery of science.

5. *Establishing global synthesis efforts*. There has never been a greater need for coordinated global integration and synthesis efforts in the domain of carbon cycle sciences. Because the carbon cycle is deeply interconnected through multiple processes in the land, oceans, atmosphere, and anthroposphere (human activities), scientific progress requires a significant investment in bringing together diverse pieces of science and regions into a common framework for analyses. Targeted synthesis efforts need to be aligned and coordinated with the Intergovernmental Panel on Climate Change (IPCC). New collaborative synthesis studies can be modeled on the successful 'Annual update of the Global Carbon Budget' and the 'REgional Carbon Cycle Assessment and Processes (RECCAP)'. A new assessment on the magnitude and vulnerability of the Earth's carbon pools is needed.
6. *Communicating the science and policy alignment*. Engagement in the climate change debate and alignment of research with policy processes are both critical for effective interactions between science, policy and society. Key engagement opportunities at the international level arise through the participation in technical panels of the United Nations Framework Convention on Climate Change and the Group on Earth Observations, as well as with regional and national policy institutions and processes. There is a continuing need for engagement with the broader society, through media releases of new research findings and informed comment on the broader scientific agenda.

Acknowledgements
JGC and MRR acknowledge and thank the support of the Australian Climate Change Science Program (ACCSP) for the Global Carbon Project office in Canberra. The ACCSP is funded jointly by the Department of Climate Change and Energy Efficiency, the Bureau of Meteorology, and CSIRO.

References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Raupach MR, Canadell JG: **Carbon and the anthropocene**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.04.003, this issue.

2. Leemans R, Asrar G, Busalacchi A, Canadell J, Ingram J, Larigauderie A, Mooney M, Nobre C, Rice M, Schmidt F: **Developing a common strategy for integrative global environmental change research and outreach: the Earth System Science Partnership (ESSP)**. *Curr Opin Environ Sust* 2009, **1**:4-13 doi: 10.1016/j.cosust.2009.07.013.

3. • Global Carbon Project: **Science framework and implementation**. *Earth System Science Partnership Report No. 1; GCP Report No. 1*. Edited by Canadell JG, Dickinson R, Hibbard K, Raupach M, Young O: Canberra; 2003:69
Comprehensive research agenda of the carbon cycle with emphasis on the interactions between the carbon cycle, human activity, and the climate system.

4. •• Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G: **Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks**. *Proc Natl Acad Sci U S A* 2007, **104**:18866-18870 doi: 10.1073/pnas.0702737104.
Decomposition of the global drivers explaining the acceleration of atmospheric CO_2 growth starting in 2000.

5. • Le Quéré C, Rödenbeck Ch, Buitenhuis ET, Conway TJ, Langenfelds R, Gomez A, Labuschagne C, Ramonet M, Nakazawa T, Metzl N *et al.*: **Saturation of the Southern Ocean CO_2 sink due to recent climate change**. *Science* 2007, **316**:1735-1738.
The first paper showing that the Southern Ocean CO_2 sink is growing at a slower pace than the growth in atmospheric CO_2.

6. •• Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P *et al.*: **Trends in the sources and sinks of carbon dioxide**. *Nat Geosci* 2009, **2**:831-836 doi: 10.1038/ngeo689.
An update of the global carbon budget and trends of its flux components.

7. Raupach MR, Canadell JG, Le Quéré C: **Drivers of interannual to interdecadal variability in atmospheric in atmospheric CO_2 growth rate and airborne fraction**. *Biogeosciences* 2008, **5**:1601-1613.

8. Nepstad DC, Stickler CM, Soares-Filho B, Merry F: **Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point**. *Phil Trans R Soc B* 2008, **363**:1737-1746 doi: 10.1098/rstb.2007.0036.

9. Tarnocai C, Canadell JG, Mazhitova G, Schuur EAG, Kuhry P, Zimov S: **Soil organic carbon pools in the northern circumpolar permafrost region**. *Global Biogeochem Cycle* 2009, **23**:GB2023 doi: 10.1029/2008GB003327.

10. Schuur EAG, Vogel JG, Crummer KG, Lee H, Sickman JO, Osterkamp TE: **The effect of permafrost thaw on old carbon release and net carbon exchange from tundra**. *Nature* 2009, **459**: doi: 10.1038/nature08031.

11. • Krey V, Canadell JG, Nakicenovic N, Abe Y, Andruleit H, Archer D, Grubler A, Hamilton NTM, Johnson A, Kostov V *et al.*: **Gas hydrates: entrance to a methane age or climate threat?** *Environ Res Lett* 2009, **4**:034007 doi: 10.1088/1748-9326/4/3/034007.
It introduces the potential risks associated with both warming and resource extraction on the stability of methane hydrates.

12. Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wösten H, Jauhiainen J: **Current and future CO_2 emissions from drained peatlands in Southeast Asia**. *Biogeosciences* 2010, **7**:1-10.

13. • Orr JC, Fabry VJ, Aumont O, Bopp L, Doney SC, Feely RA, Gnanadesikan A, Gruber N, Ishida A, Joos F *et al.*: **Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms**. *Nature* 2005, **437**:681-686 doi: 10.1038/nature04095.
A must read on ocean acidification.

14. Feely RA, Doney SC, Cooley SR: **Ocean acidification: present conditions and future changes in a high-CO_2 world**. *Oceanography* 2009, **22**:36-47.

15. Rigby M, Prinn RG, Fraser PJ, Simmonds PG, Langenfelds RL, Huang J, Cunnold DM, Steele LP, Krummel PB, Weiss RF: **Renewed growth of atmospheric methane**. *Geophys Res Lett* 2008, **35**:L22805 doi: 10.1029/2008GL036037.

16. Dlugokencky EJ, Bruhwiler L, White JWC, Emmons LK, Novelli PC, Montzka SA, Masarie KA, Lang PM, Crotwell AM, Miller JB, Gatti LV: **Observational constraints on recent increases in the atmospheric CH_4 burden**. *Geophys Res Lett* 2009, **36**:L18803 doi: 10.1029/2009GL039780.

17. • Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine H, Heinze C, Holland E, Jacob D *et al.*: **Couplings between changes in the climate system and biogeochemistry**. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Solomon S, Qin D, Manning M.*et al.*: Cambridge, United Kingdom/New York, NY, USA: Cambridge University Press; 2007.
Overview of the global carbon cycle and its interactions with climate, including explanations on how the CO_2 and CH_4 budgets are put together.

18. King AW, Dilling L, Zimmerman GP, Fairman DM, Houghton RA, Marland G, Rose AZ, Wilbanks TJ: **Asheville (2007). The first State of the Carbon Cycle Report (SOCCR): the North American carbon budget and implications for the global carbon cycle**. *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. NC, USA: National Oceanic and Atmospheric Administration, National Climatic Data Center; 2007. 242.

19. •• Schulze ED, Luyssaert S, Ciais P, Freibauer A, Janssens IA, Soussana JF, Smith P, Grace J, Levin I, Thiruchittampalam B *et al.*: **Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance**. *Nat Geosci* 2009, **2**:842-850.
A most comprehensive analysis of a regional greenhouse gas budget.

20. •• Ciais P, Canadell JG, Luyssaert S, Chevallier F, Shvidenko S, Poussi Z, Jonas M, Peylin P, King AW, Schulze E-D *et al.*: **Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting?** *Curr Opin Environ Sust* 2010 doi: 10.1016/j.cosust.2010.06.008.
Example of how to combine top-down and bottom-up observations and modeling to constrain regional carbon budgets.

21. Le Quéré C, Canadell JG, Ciais P, Dhakal S, Patwardhan A, Raupach MR, Young OR: **An International Carbon Office to assist policy-based science**. *Curr Opin Environ Sust* 2010 doi: 10.1016/j.cosust.2010.06.010.

22. Hofmann DJ, Butler JH, Dlugokencky EJ, Elkins JW, Masarie K, Montzka SA, Tans P: **The role of carbon dioxide in climate forcing from 1979 to 2004: introduction of the Annual Greenhouse Gas Index**. *Tellus B* 2006, **58**:614-619.

23. Butler J: *The NOAA Annual Greenhouse Gas Index (AGGI)*. 2009 . (access on 10 May 2010) In: *http://www.esrl.noaa.gov/gmd/aggi*.

25. Marland G, Hamal K, Jonas M: **How uncertain are estimates of CO_2 emissions?** *Ind Ecol* 2008, **13**:4-7.

26. Knorr W: **Is the airborne fraction of anthropogenic CO_2 emissions increasing?** *Geophys Res Lett* 2009, **36**:L21710. doi:10.1029/2009GL040613.

27. • Raupach MR, Marland G, Ciais P, LeQuere C, Canadell JG, Field CB: **Global and regional drivers of accelerating CO_2 emissions**. *Proc Natl Acad Sci U S A* 2007, **14**:10288-10293.
It identifies the stagnation of the historical trend of decreasing carbon intensity of the global economy.

28. Dalsøren SB, Isaksen ISA: **CTM study of changes in tropospheric hydroxyl distribution 1990–2001 and its impact on methane**. *Geophys Res Lett* 2006, **33**: doi: 10.1029/2006GL027295.

29. Piao SL, Fang JY, Ciais P, Peylin P, Huang Y, Sitch S, Wang T: **The carbon balance of terrestrial ecosystems in China**. *Nature* 2009, **458**:U1009-U1082.

30. Scholes RJ, Monteiro PS, Sabine C, Canadell JG: **Systematic long-term observations of the global carbon cycle**. *Trends Ecol Evol* 2009, **1098**:1-4.

31. GEO Carbon Strategy: 2010, from http://igco.org/GEO-Report-Nov_final_13_Nov.pdf (accessed on 10 May 2010).

32. Raupach MR, Rayner PJ, Barrett DJ, DeFries RS, Heimann M, Ojima DS, Quegan S, Schmullius CC: **Model-data synthesis in terrestrial carbon observation: methods, data requirements and data uncertainty specifications**. *Global Change Biol* 2005, **11**: doi: 10.1111/j.1365-2486.2005.00917.

33. Rayner P: **The current state of carbon cycle data assimilation**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.05.005, this issue.

34. Huntingford C, Lowe JA, Booth BBB, Jones CD, Harris GR, Gohar LK, Meir P: **Contributions of carbon cycle uncertainty to future climate projection spread**. *Tellus B* 2009, **61**:355-360.

35. Lenton A, Codron F, Bopp L, Metzl N, Cadule P, Tagliabue A, Le Sommer J: **Stratospheric ozone depletion reduces ocean carbon uptake and enhances ocean acidification**. *Geophys Res Lett* 2009, **36**: doi: 10.1029/2009GL038227L12606.

36. Cochrane MA, Laurence WF: **Synergisms between fire, land use and climate change in the Amazon**. *Ambio* 2008, **37**:522-527.

37. •• Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin V, Doney VS, Eby M, Fung I, Govindasamy B *et al.*: **Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison**. *J Climate* 2006, **19**:3337-3353.
Modeled range of the feedback between the natural carbon cycle and climate change by the end of the 21st century as provided by the state of the art earth system models.

38. •• Khvorostyanov DV, Ciais P, Krinner G, Zimov SA, Corrad Ch, Guggenberger G: **Vulnerability of permafrost carbon to global warming. Part II: sensitivity of permafrost carbon stock to global warming**. *Tellus B* 2008, **60**:265-275.

39. •• Page SE, Siegert F, Rieley JO, Boehm HV, Jaya A, Limin S: **The amount of carbon released from peat and forest fires in Indonesia during 1997**. *Nature* 2002, **420**:61-65.
It estimates for the first time the magnitude of emissions from fires in Southeast Asian forests and peatlands during an El Nino year.

40. Ballhorn U, Siegert F, Mason M, Limin S: **Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands**. *Proc Natl Acad Sci U S A* 2009, **106**:21213-21218 doi: 10.1073/pnas.0906457106.

41. Matear RJ, Wang Y-P, Lenton A: **Land and ocean nutrient and carbon cycle interactions**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.05.009, this issue.

42. Friedlingstein P, Prentice IC: **Carbon–climate feedbacks: a review of model and observation based estimates**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.06.002, this issue.

43. Frank DC, Esper J, Raible CC, Buentgen U, Trouet V, Stocker B, Joos F: **Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate**. *Nature* 2010, **463**:527-530 doi: 10.1038/nature08769.

44. Peters GP, Marland G, Hertwich EG, Saikku L, Rautiainen A, Kauppi PE: **Trade, transport, and sinks extend the carbon dioxide responsibility of countries: an editorial essay**. *Climatic Change* 2009, **97**:379-388.

45. •• Davis SJ, Caldeira K: **Consumption-based accounting of CO_2 emissions**. *Proc Natl Acad Sci U S A* 2010, **107**:5687-5692 doi: 10.1073/pnas.0906974107.
A comprehensive global overview of the magnitude and carbon embedded in traded products, its producers, consumers, and the most important sectors involved in the trade.

46. Meyfroidt P, Lambin EF: **Forest transition in Vietnam and displacement of deforestation abroad**. *Proc Natl Acad Sci U S A* 2010, **106**:16139-16444.

47. Peters GP: **Carbon footprints and embodied carbon at multiple scales**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.05.004, this issue.

48. Midgley GF, Bond WJ, Kapos V, Ravilious C, Scharlemann JPW, Woodward FI: **Terrestrial carbon stocks and biodiversity: key knowledge gaps and some policy implications**. *Curr Opin Environ Sust* 2010 doi: 10.1016/j.cosust.2010.06.001.

49. Obersteiner M, Böttcher H, Yamagata Y: **Terrestrial ecosystem management for climate change mitigation**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.05.006, this issue.

50. Crutzen PJ, Mosier AR, Smith KA, Winiwarter W: **N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels**. *Atmos Chem Phys* 2007, **8**:389-395.

51. Jackson RB, Randerson JT, Canadell JG, Anderson RG, Avissar R, Baldocchi DD, Bonan GB, Caldeira K, Diffenbaugh NS, Field CB, Hungate BA, Jobbágy EG, Kueppers LM, Nosetto MD, Pataki DE: **Protecting climate with forests**. *Environ Res Lett* 2008, **3**:044006 doi: 10.1088/1748-9326/3/4/044006.

52. Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, Hayhoe K, Avissar R, Curran LM, Friedlingstein P, Jones CD, Nobre C: **Tropical forests and climate change**. *Science* 2007, **316**:985-986.

53. Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A: **Combined climate and carbon–cycle effects of**

large-scale deforestation. *Proc Natl Acad Sci U S A* 2007, **104**:6550-6555 doi: 10.1073/pnas.0608998104.

54. Swanna AL, Fung IY, Levis S, Bonan GB, Doney SC: **Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect**. *Proc Natl Acad Sci U S A* 2010, **107**: 1295-1300 doi: 10.1073/pnas.0913846107.

55. Pongratz J, Reick CH, Raddatz T, Claussen M: **Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change**. *Geophys Res Lett* 2010, **37**: doi: 10.1029/2010GL043010.

56. Anderson RG, Canadell JG, Randerson JT, Jackson RB, Hungate BA, Baldocchi DD, Ban-Weiss GA, Bonan GB, Caldeira K, Cao L: **Biophysical considerations in forestry for climate protection**. *Front Ecol Environ* 2010 doi: 10.1890/090179.

57. Baiocchi G, Minx J, Hubacek K: **The impact of social factors and consumer behavior on carbon dioxide emission in the United Kingdom: a regression based on input–output and geodemographic consumer segmentation data**. *J Ind Ecol* 2010, **14**:50-72.

58. Lenzen M, Peters GM: **How city dwellers affect their resource hinterland: a spatial impact study of Australian households**. *J Ind Ecol* 2010, **14**:73-90.

59. Dhakal S: **GHG emissions from urbanization and opportunities for urban carbon mitigation**. *Curr Opin Environ Sust* 2010:doi:10.1016/j.cosust.2010.05.007, this issue.

60. Dhakal S, Shrestha RM: **Bridging the research gaps for carbon emissions and their management in cities**. *Energy Policy* 2009 doi: 10.1016/j.enpol.2009.12.001.

61. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T: **The next generation of scenarios for climate change research and assessment**. *Nature* 2010, **463**: doi: 10.1038/nature08823.

62. Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA,
• Meinshausen M, Meinshausen N: **Warming caused by cumulative carbon emissions: towards the trillionth tonne**. *Nature* 2009, **458**:1163-1166.

A probabilistic approach to assess the impact of a given CO_2 cumulative target on global temperature.

63. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR: **Greenhouse-gas emission targets for limiting global warming to 2°C**. *Nature* 2009, **458**:1158-1162.

64. Weber CL, Peters GP, Guan D, Hubacek K: **The contribution of Chinese exports to climate change**. *Energy Policy* 2008, **36**:3572-3577.