BRIDGING POLITICAL EXPECTATIONS AND SCIENTIFIC LIMITATIONS IN CLIMATE RISK MANAGEMENT – ON THE UNCERTAIN EFFECTS OF INTERNATIONAL CARBON SINK POLICIES*

EVA LÖVBRAND

Environmental Science Section, Department of Biology and Environmental Science, Kalmar University, SE-391 82 Kalmar, Sweden
E-mail: eva.lovbrand@hik.se

Abstract. Despite great advances in carbon cycle research during the past decade the climatic impact of terrestrial ecosystems is still highly uncertain. Although contemporary studies suggest that the terrestrial biosphere has acted as a net sink to atmospheric carbon during the past two decades, the future role of terrestrial carbon pools is most difficult to foresee. When land use change and forestry activities were included into the Kyoto Protocol in 1997, the requirements for scientific precision increased significantly. At the same time the political expectations of carbon sequestration as climate mitigation strategy added uncertainties of a social kind to the study of land-atmosphere carbon exchange that have been difficult to address by conventional scientific methods. In this paper I explore how the failure to take into account the effects of direct human activity in scientific projections of future terrestrial carbon storage has resulted in a simplified appreciation of the risks embedded in a global carbon sequestration scheme. I argue that the social limits to scientific analysis must be addressed in order to accommodate these risks in future climate governance and to enable continued scientific authority in the international climate regime.

Human-induced carbon sinks or so-called land-use and forestry (LULUCF) activities have played a dual role in the international climate regime. Although the promise of cost-effective carbon storage in biomass and soils contributed to a successful allocation of emission reduction targets during the Kyoto negotiations in 1997 and similarly helped to protect the Kyoto Protocol from unravelling in Bonn four years later, biological sinks represent one of the most contested and hence obstructive issues in the climate negotiation process. The objections to LULUCF activities have often referred to the equity aspirations in the United Nations Framework Convention on Climate Change (FCCC) and industrialised countries' moral responsibility to take the lead in long-term emission reductions (UN, 1992, Article 3). Already in Kyoto several negotiating parties suggested that an inclusion of carbon sinks into the Kyoto Protocol would function as a loophole that will delay a stabilisation of atmospheric CO_2 levels and the long-term aim to curb climate change. By highlighting the large land areas with actual or potential carbon uptake within industrialised

---

*This article was initiated in connection with the International Workshop on "Quantifying Terrestrial Carbon Sinks: Science, Technology and Policy", held in Wengen September 25–27 2002.

Climatic Change **67:** 449–460, 2004.
© 2004 *Kluwer Academic Publishers. Printed in the Netherlands.*

countries, it was argued that terrestrial sinks would limit the efforts to reduce greenhouse emissions and hence leave the door open for business-as-usual (Grubb et al., 1999). Scientific uncertainty is closely connected to this concern. Despite great advances in carbon cycle research during the 1990s, sink critics have throughout the negotiation process feared that the prevailing difficulties to accurately monitor and verify terrestrial carbon exchange will indirectly encourage parties to exaggerate national carbon removals and thereby undermine the effectiveness and credibility of the Kyoto Protocol (Noble and Scholes, 2001; Schulze et al., 2002). In order to overcome this compromising uncertainty, provisions for eligible carbon removals have been subject to intensive negotiations since 1997 and are now represented by a complex set of definitions and accounting rules in relation to Articles 3.3 and 3.4 of the Kyoto Protocol.

Does the agreement on the Kyoto Protocol in Bonn and Marrakech in 2001 imply that the political controversies and scientific uncertainties surrounding sinks are settled? In the following paper I will question this assumption by exploring some of the challenges to contemporary research on terrestrial carbon exchange. To account for all natural drivers behind carbon storage in terrestrial ecosystems and the effects of anthropogenic disturbance is indeed a highly complex endeavour that has been fraught with great uncertainty since measurements were first initiated. The political requirements included in Articles 3.3 and 3.4 have increased the complexity significantly and added a direct political dimension to scientific sink studies. I here explore how this shift to politically mandated science has brought uncertainties of a social kind into the light. Although these ‘new’ uncertainties so far have intensified research, they may in a longer-term perspective undermine both the authority of scientific advice and the legitimacy of LULUCF activities in the international climate regime. In order to characterise this social challenge to carbon sink research and the risks it poses to international climate governance, a theoretical account of uncertainty and risk is necessary.

1. From Uncertainty to Indeterminacy – The Social Dimension of Environmental Risks

Environmental problems referred to as global often involve large-scale, highly complex and non-linear interactions between biogeochemical cycles, ecosystem processes and human society. Since the sources and effects of these problems often are diffuse and vary largely over temporal and geographical scales they are difficult to measure, predict and value. This has in turn called for new ways of addressing and conceptualising risks (Kaspersen and Kaspersen, 2001; The Social Learning Group, 2001). When risk assessment was developed as a scientific method in the 1960s, it was primarily used to analyse safety problems generated by chemical and nuclear technologies (Morgan and Henrion, 1998). Scientists engaged in risk assessment would anticipate the consequences of technical hazards, and analyse the likelihood of adverse effects over time and space (Renn, 1992). In this technical kind of risk analysis, *risk* is defined as probability times consequence and used as the rational basis for societal management of undesirable effects. Although risk by definition involves uncertainty, the high complexity of global environmental change has introduced a range of new uncertainties that challenge the reliability and hence automatic rationality of scientific advice in the management of environmental problems.

Anthropogenic climate change is a good example of a contemporary environmental issue for which uncertainties have been most difficult to address by conventional scientific methods. Besides the inherent complexity of the climate system, scientists are faced with a large series of conditionalities of a social kind that do not easily lend themselves to prediction (Grübler and Nakicenovic, 2001). These social uncertainties (*inter alia*, socio-economic development, demographic trends, future land use practices, international policy-making) should not be mistaken for simply larger-scale uncertainty in a technical sense but rather contain *indeterminate* features that in many ways fall beyond the frames of conventional scientific analysis (Wynne, 1992). Since all scientific representations of climate risks are conditional to pre-analytical assumptions about how a range of social actors will behave in the future, and hence are mediated by prior experiences and expectations, they cannot be divorced from the social and political context in which they are produced. This constructionist approach to environmental risks does not reject the reality or severity of environmental problems such as climate change (Jones, 2002). The concern is rather that scientists involved in risk assessment tend to treat indeterminate environmental problems as traditional uncertainties and therefore call for more research as the way to address environmental risks. This tendency to reduce social conditionalities to technical and methodological uncertainties reveals a built-in ignorance in science towards its social limits that can be most dangerous if it is reproduced among policy-makers who base important decisions on scientific results (Wynne, 1992; Funtowicz and Ravetz, 2001). If the ability of science to provide comprehensive and value-neutral assessments of climate risks is exaggerated, scientific results may either be given a disproportional influence over societal decision-making or be used as an effective means for decision-makers to neutralise and hence legitimise politically charged decisions (Miller, 2001). In either case, the public debate on societal response strategies to anthropogenic climate change is severely restricted which in itself constitutes a fundamental risk to democratic policy-making.

The introduction of social indeterminacies to scientific analysis calls for greater scrutiny of the risks of anthropogenic climate change. In the early 1990s the German sociologist Ulrich Beck introduced the concept *reflexive modernisation*, referring to a re-conceptualisation of the risks generated by modern industrialised society (1992). In the management of global environmental threats, Beck suggests that modern society needs to acknowledge the limits of scientific inquiry and move towards new forms of rationality. More science in the conventional sense is hence not the primary way to cope with ‘ecological mega-hazards’ such as climate change (Beck, 2001). Rather, the substantive controversies over methods, calculation procedures, norms and routines generated by global environmental threats will necessitate a fundamental revision of scientific practice. While Beck sees this radical self-confrontation of science as an inevitable or *reflexive* result of risk society and the profound institutional crisis this phase of modernity will generate, *reflexive scientisation* by necessity involves *self-reflection* (Beck, 1994). Although a great deal of contemporary climate science has been focused on reducing uncertainty, self-reflection in this case implies an acknowledgement of irreducible uncertainties and a thorough and public discussion about their potential consequences. The large political interest in carbon sequestration as a climate mitigation measure has in recent years put great pressure on scientists to deliver results that can move the negotiation process forward and legitimise generous sink provisions in the Kyoto Protocol. Although there are pragmatic reasons for scientists to provide requested policy advice and not letting uncertainty delay the negotiation process, there are cases when it is entirely risky to downplay uncertain outcomes (Hansson, 1999). When addressing the many uncertainties and social indeterminacies embedded in the scientific study of terrestrial carbon sequestration, it becomes clear that LULUCF activities indeed represent such a case. In the following section I hence aim to contribute to a reflexive and interdisciplinary discussion by addressing some of these risks. I particularly explore two issues that have gained political importance in the negotiations over Articles 3.3 and 3.4 and therefore also have been subject to much research since the Kyoto negotiations. These concerns include the political requirement to distinguish direct human-induced carbon uptake from natural fluxes and to determine the long-term fate of carbon stored in biomass and soils.

2. Uncertain Terrestrial Carbon Sinks and the Kyoto Protocol

During the third conference of the parties (COP3) to the UNFCCC in Kyoto in 1997, industrialised countries agreed to cut national greenhouse gas emissions by on average 5.2% during the period 2008–2012 using the emissions in 1990 as the baseline. Article 3.3 in the Kyoto Protocol specifies this commitment to *net* changes in greenhouse gas emissions and hence allows industrialised parties to account for “removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990” (UN, 1997). Since the resumed COP6 in Bonn in 2001, Article 3.4 of the protocol also opens up for removals resulting from human-induced revegetation, forest management, cropland management and grazing land management (UNFCCC/CP/2001/L.11/Rev.1). The scope of land-use change and forestry activities included in the Kyoto Protocol has since 1997 represented a compromise between two opposing political positions in the climate negotiations. On one end of the political scale the negotiating parties that have perceived sinks as a cost-effective alternative to emission reductions and therefore have favoured an unrestricted or full carbon accounting of terrestrial uptake are found (notably USA, Canada, Australia). As suggested by US negotiators in Kyoto, removals of atmospheric CO_2 do not only offer the same climatic effect as emission reductions but also do so at a significantly lower societal cost (Grubb et al., 1999). For the EU, some developing country parties and most environmental NGOs sinks have on the other hand been viewed as an obstacle on the way towards an inevitable decarbonisation of industrial society, and since the Kyoto negotiations these parties have thus tried to limit the range of eligible LULUCF activities in the Kyoto Protocol (Grubb et al., 1999; Schulze et al., 2002). The reference to *direct-human induced* carbon uptake in Article 3.3 is an example of the compromise between these two polarised positions. The wording was adopted as a safeguard against business as usual, and is essentially devised to restrict eligible carbon uptake to sinks that are deliberately created or enhanced in order to meet the Kyoto commitments. Although the reference to direct human induced carbon removals was necessary for a political agreement over Article 3.3 during the Kyoto negotiations, it generated unforeseen and perhaps even unforeseeable scientific problems.

2.1. NATURAL VS HUMAN-INDUCED CARBON UPTAKE

Any measurement of direct human-induced carbon uptake requires an interpretation of what is to be considered directly human induced. Since all parts of the globe are more or less affected by human activity a broad interpretation would classify the entire terrestrial biosphere as a potential sink under the Kyoto Protocol (Schulze et al., 2002). However, by specifying eligible carbon uptake to afforestation, reforestation and deforestation, the negotiating parties have restricted the interpretations of Article 3.3 significantly. Apart from distinguishing carbon sequestered in ‘Kyoto forests and lands’ from carbon stored in unmanaged ecosystems, parties to the Kyoto Protocol are also required to factor out sequestration caused by elevated atmospheric CO_2 levels, nitrogen deposition and anthropogenic climate change from eligible carbon removals (UNFCCC/CP/2001/L.11/Rev.1). Both types of distinctions are problematic from a scientific perspective.

As suggested by the atmospheric data included in the IPCC’s most recent global carbon budget (see Table I), the terrestrial biosphere was a net sink for atmospheric CO_2 during the 1980s and 1990s (Prentice et al., 2001). In order to identify the human contribution to this inferred land-atmosphere flux, the IPCC has included human land-use data in the global equation. This complementary information is primarily derived from national land-use statistics and biomass inventories, and accounts for global fluxes of carbon dioxide generated by human land cover change (Prentice et al., 2001). Since figures on global land-use during the 1990s were not available when IPCC prepared its Third Assessment Report, Table I has been updated with data from a more recent study (Houghton, 2003).

TABLE I

Global carbon budgets for 1980s and 1990s in GtC/yr (Prentice et al., 2001; Houghton, 2003)

	1980s	1990s
Atmospheric increase	3.3 (±0.1)	3.2 (±0.1)
Emissions (fossilfuel, cement)	5.4 (±0.3)	6.3 (±0.4)
Ocean-atmosphere flux	−1.9 (±0.6)	−1.7 (±0.5)
Land-atmosphere flux[*]	−0.2 (±0.7)	−1.4 (±0.7)
[*]Partitioned as:		
Land-use change[b]	2.0 (±0.8)	2.2 (±0.8)
Residual terrestrial sink[b]	−2.4 (±1.1)	−2.9 (±1.1)

[a] Positive values are fluxes to the atmosphere; negative values represent uptake from the atmosphere. Values within parenthesis denote uncertainty, not interannual variability which is substantially higher.

[b] From Houghton (2003).

As indicated in Table I global land use change generated a net carbon source both during the 1980s and 1990s. These estimates represent a global balance between the amounts of carbon lost through deforestation (primarily in tropical regions) and carbon accumulated in newly planted and recovered forests (primarily in the Northern Hemisphere) (Houghton, 2002, 2003). The substantial uncertainty range for land-use emissions during these two decades is mainly explained by inconsistencies in national forest definitions and inventory methods as well as by the lack of regular inventory data from developing countries (Prentice et al., 2001; Houghton, 2002, 2003). Although much scientific effort in recent years has aimed at reducing these methodological uncertainties in order to provide reliable measurements of national carbon removals (Bolin and Sukumar, 2000), a fundamental problem facing scientists involved in the monitoring and verification of eligible sinks under the Kyoto Protocol is to prove that the carbon uptake measured in land-use studies actually are *directly* human-induced. As suggested in Table I the net terrestrial carbon uptake in the 1980s and 1990s was due to an unspecified residual terrestrial sink inferred from atmospheric data. For some time scientists have assumed that indirect human effects such as enhanced levels of CO_2 in the atmosphere and nitrogen deposition stimulate global plant growth and hence contribute to this residual carbon uptake (Warrick et al., 1986; Melillo et al., 1996; Prentice et al., 2001). Recent data also suggest that nitrogen deposition suppresses decomposition of carbon in soils leading to a gradual build-up of soil organic C pools (van Oene et al., 2000). Natural biomass regeneration in former agricultural lands and extended growth seasons caused by natural and human-induced variations in climate are used as additional explanations of the unspecified terrestrial carbon uptake or the so-called ‘missing sink’ (Houghton, 2002, 2003; Prentice et al., 2001). Even though a range of methodological approaches are used in combination so as to separate direct human effects from the sum of indirect human or natural effects, a full separation at site or ecosystem level is still unattainable due to the multitude of factors and processes in play (Schimel and Manning, 2003). From a strictly climatic perspective the inadequate attribution may not be necessarily important. It could easily be argued that carbon uptake generated by CO_2 or N-fertilisation contributes to an equally valuable reduction of atmospheric carbon as do deliberate land-use practices (although the future evolution of that sink maybe quite different). However, politically this shortcoming is problematic. Since the parties to the Climate Convention have agreed to accept only deliberately created sinks, the failure to separate direct anthropogenic carbon uptake from indirect human or natural sequestration will limit an accountable or 'fair' implementation of the Kyoto Protocol. The distinction between natural and human impacts on terrestrial carbon pools is also politically relevant by indicating what type of uncertainties and risks that are built into Articles 3.3 and 3.4 of the Kyoto Protocol.

2.2. FUTURE CARBON STORAGE IN TERRESTRIAL ECOSYSTEMS

Will the terrestrial biosphere continue to be a net carbon sink in the future and what will happen to the carbon stored in biomass and soils by LULUCF activities? Until now, many scientific studies have forwarded a beneficial picture of terrestrial carbon storage and suggested that biological sinks represent finite but important reservoirs that can buy time for the development of low-emission technologies during the coming decades (Noble and Scholes, 2001; IGBP, 1998; Schlamadinger and Marland, 2000; Kauppi and Sedjo, 2001). The projections have primarily rested on an analysis of the natural mechanisms responsible for the current carbon uptake and the extent to which these are expected to persist in the future. Also historic changes in land use have been used when estimating future terrestrial carbon uptake (Houghton, 2002). Since the amount of carbon released through human land use change globally between 1850 and 1998 (136 ± 55 GtC) corresponds to approximately half of the carbon emitted from fossil fuel burning and cement production during the same time period (Bolin and Sukumar, 2000), recovery from past disturbances could have a substantial balancing effect on the climate system during the coming century. Although promising, this benign representation of terrestrial carbon storage is highly unreliable since it only accounts for historic human disturbance.

Human activity has altered terrestrial carbon pools substantially during past centuries and can be expected to do so also in the future. First of all the indirect human effects of anthropogenic climate change may be become more important than previously assumed. In recent years models have been developed in order to account for potential feedbacks between human-induced climate change and ecosystem processes (Prentice et al., 2001). The complexity of these 'coupled' climate-carbon cycle models has until now limited scenario reliability, but the model results are important since they suggest that large risks may be embedded in an extensive use of LULUCF activities. Although higher temperatures and elevated CO_2 levels in the atmosphere are expected to prolong growth seasons in most temperate and arctic ecosystems and hence increase carbon storage in these regions, a growing number of coupled models have projected that terrestrial carbon uptake will be counteracted by enhanced soil respiration and potential forest dieback in water stressed ecosystems. In scenarios produced by several dynamic global vegetation models (DGVM), net terrestrial carbon uptake declines by 2050 due to increased heterotrophic respiration and ecosystem response to regional precipitation shifts in Africa, America and South-East Asia (Cramer et al., 2001). Other coupled models project a more rapid release of carbon from soils as temperature increases, turning the terrestrial carbon cycle into a substantial global net source beyond 2050 (Cox et al., 2000; Jones et al., 2003; White et al., 1999). Even though it is important to acknowledge the uncertainty surrounding these scenarios, the climate sensitivity of terrestrial carbon pools constitutes a serious challenge to LULUCF activities as long-term climate mitigation options for the international climate regime. Adding the potential effects of direct land use changes to the equation, the positive framing of sinks is further challenged. During the 1980s conversion and management of tropical forests were responsible for approximately 27% of the annual carbon emissions on a global scale (Houghton, 2003). Recent studies indicate that tropical deforestation rates and ensuing carbon losses increased during 1990s, whereas land use management resulted in an net accumulation of carbon in the Northern hemisphere during the same time period (Houghton, 2003). Although science cannot be expected to predict the long-term effects of these inherently indeterminate human activities, social uncertainties associated with human land use must be considered when evaluating the benefits and risks built into a global sequestration scheme. A complete conversion of global forests to grasslands could theoretically emit 400 to 800 GtC to the atmosphere (Schimel and Manning, 2003), the latter estimate representing almost double the amount of carbon dioxide emitted as a result of fossil fuel burning, cement production and land use change since 1850 (Bolin and Sukumar, 2000). Although a global forest loss of this magnitude is very unlikely, it highlights the risks of relying too heavily on reversible sinks in the international climate regime. However, by omitting possible future human disturbance from the analysis, contemporary studies of terrestrial carbon uptake have so far downplayed the risks embedded in LULUCF activities and hence contributed to a simplistic understanding of Articles 3.3 and 3.4 in the Kyoto Protocol.

3. Bridging Political Expectations and Scientific Limitations

It is not difficult to appreciate the political effect that the primarily positive scientific scenarios of terrestrial carbon storage have had in the climate negotiation process. In all industrialised countries GHG emissions have increased significantly since 1990, and LULUCF activities have hence become an increasingly important instrument for many of the parties to the Kyoto Protocol when meeting their commitments. Although the reversibility of biological sinks has been acknowledged as a problem among the negotiating parties and generated discussions about how to allocate responsibility for LULUCF activities beyond the first commitment period (Marland et al., 2001), sink critics have since the US withdrawal from the Kyoto process been put under greater pressure to overlook the potential risks built into the agreement. At the resumed COP6 in Bonn in 2001 LULUCF activities became subject to a larger compromise aimed at ‘saving the protocol’ and the meeting ended with an agreement over more generous sink provisions than previously envisioned by the EU and G77/China (Schulze et al., 2002). At COP7 in Marrakech in November 2001 the negotiating parties also agreed on a very short-term compliance mechanism for the Kyoto Protocol which made responsibility for sinks created under the protocol conditional to a second commitment period (Schulze et al., 2002). Although this provisional rule was necessary for a political settlement over the Kyoto Protocol in Marrakech, it opens up for a range of uncertainties that undermines the promising framing of LULUCF activities. Beyond the significant risks of a large-scale release of terrestrial carbon due to climate change, future land use changes could potentially threaten the long-term stability of carbon sequestered within the frames of the Kyoto Protocol. The extent to which the current compliance regime will be able to accommodate human induced carbon releases beyond 2012 is still unclear, a circumstance that strongly questions the long-term effectiveness and legitimacy of LULUCF activities as climate mitigation strategy.

The extended risk picture also raises important questions about the future role of scientific advice in the international climate regime. Although continued research in the conventional sense is required in order to reduce methodological uncertainties in the verification of national carbon removals, a more interdisciplinary approach will be needed in order to include human impacts into scenarios of future terrestrial carbon exchange. At the same time it is important to acknowledge that the range of social conditionalities driving future human land use practices challenges the idea that science ever will be able to reduce all uncertainties and arrive at a comprehensive and value neutral representation of LULUCF activities and the risks built into Articles 3.3 and 3.4. This conclusion questions the deeply held assumption that more scientific knowledge is the most rational basis for policy-making (Shackley and Wynne, 1996), and hence calls for *reflexiveness* towards policy-decisions legitimised by scientific results. To prevent that the risks embedded in LULUCF activities are overlooked or downplayed with reference to scientific results in future climate governance, a more *self-reflective* analysis and representation of uncertainties in the scientific study of terrestrial carbon exchange is necessary. Addressing social limitations to scientific practice should thus be viewed as a way to ensure rather than undermine continued scientific authority in the international climate regime.

Acknowledgements

This paper arises out of research funded by the Graninge Foundation and the Natural Science Faculty Board at Kalmar University in Sweden. A special thanks to Bo Wiman and three reviewers for their constructive and valuable comments on earlier versions of this paper.

References

Beck, U.: 1992, *Risk Society. Towards a New Modernity*, Sage Publications, London.

Beck, U.: 1994, 'The reinvention of politics: Towards a theory of reflexive modernisation', in Beck, U., Giddens, A., and Lash, S. (eds.), *Reflexive Modernization. Politics, Traditions and Aesthetics in the Modern Social Order*, Standford University Press, Standford.

Beck, U.: 2001, 'From industrial society to risk society', in Dryzek, J. S. and Schlosberg, D. (eds.), *Debating the Earth. The Environmental Politics Reader*, Oxford University Press, Oxford, New York.

Bolin, B. and Sukumer, R. (eds.): 2000, 'Global perspective', in Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J., and Dokken, D. J. (eds.), *Land Use, Land-Use Change, Forestry, A Special Report of the IPCC*, Cambridge University Press, Cambridge.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. and Totterdell, I. J.: 2000, 'Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model', *Nature* **409**, 184–187.

Cramer, W., Boneau, A., Woodward, I. F., Prentice, I. C., Betts, R. A., Browkin, V., Cox, P. M., Fisher, V., Foley, J. A., Friend, A. D., Kucharik, C., Lomas, M. R., Rmankutty, N., Sitch, S., Smith, B., White, A. and Young-Molling, C.: 2001, 'Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results from six dynamic global vegetation models', *Global Change Biology* **7**, 357–373.

Funtowicz, S. O. and Ravtez, J. R.: 2001, 'Global risk, uncertainty, and ignorance', in Kasperson, J. X. and Kasperson, R. E. (eds.), *Global Environmental Risk*, United Nations University Press, Tokyo.

Grubb, M., Vrolijk, C. and Brack, D.: 1999, *The Kyoto Protocol. A Guide and Assessment*, The Royal Institute of International Affairs, London.

Grübler, A. and Nakicenovic, N.: 2001, 'Identifying dangers in an uncertain climate', *Nature* **412**, 15.

Hansson, S. O.: 1999, 'A philosophical perspective on risk', *Ambio* **28**, 539–542.

Houghton, R. A.: 2002, 'Magnitude, distribution and causes of terrestrial carbon sinks and some implications for policy', *Climate Policy* **2**, 71–88.

Houghton, R. A.: 2003, 'Revised estimates of the annual net flux of carbon to the atmosphere from changes in land management 1850–2000', *Tellus* **55B**, 378–390.

IGBP Terrestrial Carbon Working Group: 1998, 'The terrestrial carbon cycle: Implications for the Kyoto Protocol', *Science* **280**, 1393–1394.

Jones, C., Cox, P. and Huntingford, C.: 2003, 'Uncertainty in climate-carbon cycle projections associated with the sensitivity of soil respiration to temperature', *Tellus* **55B**, 642–648.

Jones, S.: 2002, 'Social construtionism and the environment: Through the quagmire', *Global Environmental Change* **12**, 247–251.

Kasperson, J. X. and Kasperson, R. E. (eds.): 2001, *Global Environmental Risk*, United Nations University Press, Tokyo. Kauppi, P. and Sedjo, R.: 2001, 'Technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineerin', in Metz, B., Davidson, O., Swart, R., and Pan, J. (eds.), *Climate Change 2001: Mitigation,* *Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Marland, G., Fruit, K. and Sedjo, R.: 2001, 'Accounting for sequestered carbon: the question of permanence', *Environmental Science and Policy* **4**, 259–268.

Melillo, J. M., Prentice, I. C., Farquar, G. D., Shulze, E.-D. and Sala, O. E.: 1996, 'Terrestrial biotic responses to environmental change and feedbacks to climate', in Houghton, J. T., Filho, M. L. G., Callander, B. A., Harris, N., Kattenberg, A. and Maskell, K. (eds.), *Climate Change 1995. The Science of Climate Change. Contritbution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Miller, C. A.: 2001, 'Challenges in the application of science to global affairs', in Miller, C. A. and Edwards, P. N. (eds.), *Changing the Atmosphere. Expert Knowledge and Environmental Governance*, The MIT Press, Cambridge, London.

Morgan, M. G. and Henrion, M.: 1998, *Uncertainty. A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, Cambridge University Press, New York.

Noble, I. and Scholes, R. J.: 2001, 'Sinks and the Kyoto Protocol', *Climate Policy* **1**, 5–25.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., and Wallace, D. W. R.: 2001, 'The carbon cycle and atmospheric carbon dioxide', in Hougthon, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.), *Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Renn, O.: 1992, 'Concepts of risk: A classification', in Krimsky, S. and Golding, D. (eds.), *Social Theories of Risk*, Praeger, Westport, London.

Schimel, D. and Manning, M. (eds.): 2003, *IPCC Meeting on Current Scientific Understanding of the Processes Affecting Terrestrial Carbon Stocks and Human Influences upon Them*, IPCC Working Group 1 Technical Support Unit, NOAA, Boulder.

Schlamadinger, B. and Marland, G.: 2000, *Land Use & Global Climate Change. Forests, Land Management, and the Kyoto Protocol*, Pew Center on Global Climate Change, Arlington, U.S.A.

Schulze, E.-D., Valentini, R. and Sanz, M.-J.: 2002, 'The long way from Kyoto to Marrakesh: Implications of the Kyoto Protocol negotiations for global ecology', *Global Change Biology* **8**, 505–518.

Shackley, S. and Wynne, B.: 1996, 'Representing uncertainty in global climate change science and policy: Boundary-ordering devices and authority', *Science, Technology & Human Values* **21**(3), 275–302.

The Social Learning Group, 2001, *Learning to Manage Global Environmental Risks. A Functional Analysis of Social Responses to Climate Change, Ozone Depletion, and Acid Rain*, MIT Press, Cambridge, London.

Van Oene, H., Berendse, F., Persson, T., Harrison, A. F., Schulze, E.-D., Andersen, B. R., Bauer, G. A., Dambrine, E., Högberg, P., Matteucci, G. and Paces, T.: 2000, 'Model analysis of carbon and nitrogen cycling in *Pincea* and *Fagus* forests', in Schulze, E.-D. (ed.), *Carbon and Nitrogen Cycling in European Forest Ecosystems*, Springer Verlag, Berlin Heidelberg.

Warrick, R. A., Shugart, H. H., Antonovsky, M. J., Tarrant, J. R. and Tucker, C. J.: 1986, 'The effects of increased CO_2 and climatic change on terrestrial ecosystems', in Bolin, B., Döös, B. R., Jäger, J. and Warrick, R. A. (eds.), *The Greenhouse Effect, Climatic Change, and Ecosystems*, Published on behalf of the Scientific Committee on Problems of the Environment (SCOPE), Wiley & Sons, New York.

White, A., Cannell, M. G. R. and Friend, A.: 1999, 'Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment', *Global Environmental Change* **9**, S21–S30.

Wynne, B.: 1992, 'Uncertainty and environmental learning. Reconceiving science and policy in the preventive paradigm', *Global Environmental Change* 111–127.

United Nations(UN), 1992, *Framework Convention on Climate Change*, UNEP/IUC/99/9, Bonn.

United Nations(UN), 1997, *Kyoto Protocol to the Framework Convention on Climate Change*, UNEP/IUC/98/2, Bonn.

(Received 13 May 2003; in revised form 9 April 2004)