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TELLUS

Implications of land ecosystem-atmosphere interactions for strategies for climate change adaptation and mitigation

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ABSTRACT

The standard approach to predicting climate change, assessing its impacts and planning mitigation strategies tends to be compartmentalized, leading to inadequate or incomplete advice for climate policy. Climate models used for future global warming predictions and attribution of past changes generally consider only global climate drivers, ignoring local drivers, such as land use change and urban effects. Impacts studies are generally carried out in isolation from each other and hence ignore interactions between different impacts sectors, such as hydrology, natural ecosystems and agriculture. Feedbacks from impacts to climate change, which often involve land ecosystem-atmosphere interactions, are often neglected. This can result in representations of global changes that are at best inconsistent and at worst completely misleading. Moreover, a number of climate change mitigation strategies, such as carbon sequestration and biofuels involve changes in land ecosystems. In addition to affecting climate through the exchange of carbon with the atmosphere, these land ecosystem changes may affect climate change or its impacts through a variety of additional processes, such as surface albedo change or changes in the surface moisture budget. Failure to account for these may have consequences that are potentially at odds with the aims of climate change mitigation.

1. Introduction

A common view depicts the process of climate change as a linear chain of causes and effects, with human activities resulting in greenhouse gas emissions which affect climate and hence cause impacts (Fig. 1a). In assessments of climate change following this conceptual model, information is passed through a sequence of models in one direction only. Some approaches are now beginning to include feedbacks from 'impacts' back to greenhouse gas (GHG) concentrations and climate (Fig. 1b) but this still not routine and often only global-scale feedbacks (such as through the carbon cycle) are considered. However, predictions at the regional scale are needed to inform strategies for adaptation. Climate models used for future climate predictions and attribution of past changes generally consider only radiative forcing by GHGs and aerosols, and ignore other drivers, such as the biogeophysical effects of land use change even when regional climate models are used (Fig. 1b). This is because the focus is on global climate change, although again regional change important for informing adaptation. Other drivers of global change, such as the direct impacts of atmospheric composition or land cover change on ecology and their interactions with hydrological impacts, are often neglected (Fig. 1b). Adaptation plans need to consider these. Moreover, if plans to mitigate climate change through reduction in net GHG emissions, for example through carbon sequestration, involve processes that also exert other impacts on the climate system, these should be taken into consideration.

Impacts studies are generally carried out in isolation from each other and hence ignore key interactions between different impacts sectors, such as hydrology, natural ecosystems and agriculture.

While these approximations may have been valid when assessing the potential need for reducing greenhouse gas emissions, a number of recent studies imply that a more integrated approach is now required to help plan adaptation and mitigation responses. Failure to exploit these new approaches may lead to erroneous judgements on the current effects of climate change, and poorly-founded plans for mitigation and adaptation.

This paper brings together recent work that takes a more integrated approach to the assessment of the impacts of climate change and related human activities, and discusses the implications for the decisions that need to be taken regarding the various responses to the climate change issue.

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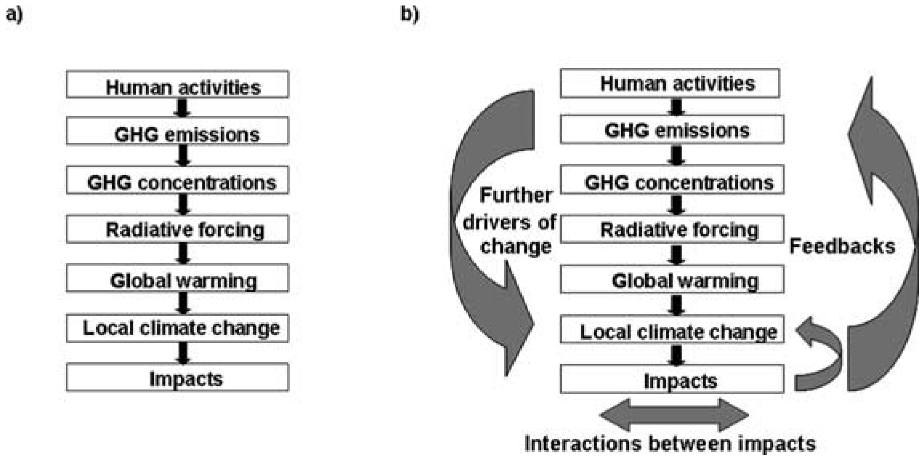

Fig. 1. (a) Conventional, linear, cause-effect conceptual model of climate change. (b) Roles of land ecosystem-atmosphere interactions.

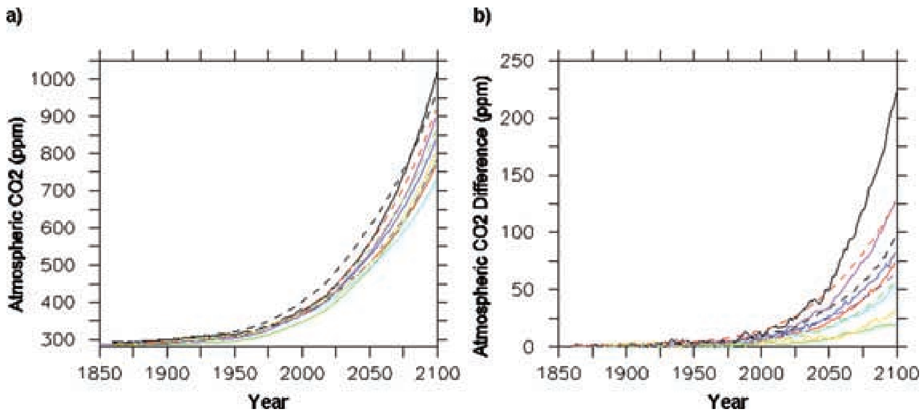

Fig. 2. Uncertainties in CO_2 concentrations associated with one emissions scenario, as a result of climate-carbon cycle feedbacks. Left panel: CO_2 concentrations simulated by the 11 'C4MIP' coupled climate-carbon cycle models driven by the SRES A2 emissions scenario, with climate-carbon cycle feedbacks included. Right panel: Differences in CO_2 concentrations between simulations including and excluding carbon cycle feedbacks, for each of the C4MIP models. In each panel, results from the Hadley Centre model HadCM3LC (Cox et al., 2000) is shown by the solid black lines. Figure reproduced from Friedlingstein et al. (2006), copyright American Meteorological Society.

2. Informing adaptation to climate change under multiple stresses

2.1. Feedbacks on global climate change

Changes in global ecosystems under climate change may themselves exert further effects on climate. Ecosystem-induced changes in well-mixed GHGs, such as CO_2 and CH_4 will exert global-scale feedbacks. For example, in the coupled climate carbon cycle version of the 3rd Hadley Centre Climate Model (HadCM3LC) Cox et al. (2000) found that climate-carbon cycle feedbacks enhanced the rate of CO_2 rise by 75% compared to CO_2 concentration projections which neglected the effect of climate change on the carbon cycle. This feedback arose mainly from an increase in worldwide soil respiration as a result of increased temperature, with a secondary (10%) contribution from die-back of forest cover in Amazonia as a consequence of reduced precipitation due to atmospheric circulation changes associated with particular patterns of warming in the North Atlantic and equatorial East Pacific. This feedback resulted in an acceleration of global warming of approximately 50% compared to climate simulations driven by CO_2 concentrations prescribed by projections that excluded the effects of climate.

Positive feedbacks on the CO_2 rise and climate change have also been found to emerge in all other coupled climate-carbon cycle models in the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP: Friedlingstein et al., 2006). The strength of the feedback varies significantly between models, with HadCM3LC showing the largest feedback (Fig. 2). There is therefore a significant uncertainty in the translation of CO_2 emissions scenarios into scenarios of CO_2 concentrations. However, this uncertainty is often neglected, and the scenarios of CO_2 *concentrations* used to drive climate models are routinely described as '*emissions* scenarios'. For example, climate model simulations are almost always described as having been driven by a particular emissions scenario from the Intergovernmental

Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), when in fact they have been driven by a scenario of CO_2 concentrations that neglected climate-carbon cycle feedbacks. The results of C4MIP clearly imply that it is incorrect to use emissions scenario names to label such simulations. With climate-carbon cycle feedbacks being of potentially great significance for projections of future global climate change, it is important to find a more informative system of identifying the assumptions made in climate projections.

2.2. *Feedbacks on regional climate change*

The nature of land cover and land use is a major influence on the physical properties of the land surface. In general, a forested landscape exhibits a lower surface albedo, a larger aerodynamic roughness and a greater availability of moisture for evaporation than a non-forested landscape. Trees significantly increase evaporation by drawing-up soil moisture and transpiring it through their leaves, and also by enhancing turbulent transport by increasing the aerodynamic roughness of the landscape. Removal of forest cover would therefore be expected to lead to decreased evaporation and a reduction in the absorption of solar radiation. When resulting from a large-scale change, these changes in land surface properties can significantly influence regional climates and wider-scale atmospheric circulations.

Changes in terrestrial ecosystems due to climate change may exert some significant feedbacks on regional climates through changes in the physical properties of the land surface. Betts et al. (2004) examined these biogeophysical feedbacks on 21st-century climate change with two simulations with HadCM3LC with CO_2 concentrations prescribed to the standard IS92a scenario neglecting climate-carbon cycle feedbacks, with one simulation including changes in vegetation cover (Fig. 3a) simulated by the TRIFFID Dynamic Global Vegetation Model (DGVM; Cox, 2001), and the other with vegetation cover fixed at the present-day state. Comparison between these therefore reveals the extent of biogeophysical feedbacks on climate change in the HadCM3LC model.

The general global patterns of climate change were similar in the two simulations, with almost all changes in temperature and precipitation being of the same sign irrespective of the inclusion of vegetation feedbacks. This implies that vegetation feedbacks are not a significant influence on atmospheric circulation in comparison with the greenhouse-gas forcing. However, some of the regional climate changes were significantly affected by vegetation feedbacks (Fig. 3b). In particular, the precipitation reduction over Amazonia was found to be enhanced by 25% by feedbacks from the loss of forest cover. In the western part of the basin, the feedback was greater still, magnifying the precipitation reduction by over 30%. The larger precipitation decrease in Western Amazonia was attributed to drought-induced die-back of the eastern forests contributing to further rainfall reductions in the west. The forest loss also increased surface albedo, which reduced convection and moisture convergence, providing a further positive feedback on rainfall reduction (Charney, 1975).

Further biogeophysical feedbacks were seen at high latititudes, with the boreal forests expanding and thickening and tundra shrub cover also expanding. The more extensive vegetation cover resulted in a lower surface albedo, which increased the absorption of solar radiation. This provided a further 1 K of warming over land north of 50 °N, in addition to the 6 K simulated with fixed vegetation cover.

Changes in vegetation cover in semi-arid climates may lead to changes in the emission of mineral dust aerosol from the land surface. These can affect climate by exerting radiative forcings in both the short wave and long wave—the net effect is complex, and depends on other factors, such as the albedo of the underlying surface. Woodward et al. (2005) used a dust emissions and transport model in the Hadley Centre climate model to simulate the changes in atmospheric dust load as a consequence of a drying climate and forest die-back in Amazonia as simulated by HadCM3LC (Cox et al., 2000; Betts et al., 2004). By 2100, Amazonia was simulated to become a source of dust equivalent to that of the present-day Sahara desert (Fig. 4a,b), as a result of dry soil, exposure of soil by lost forest cover, and increased wind speed that was a consequence of the reduced aerodynamic roughness of the landscape. This resulted in a positive radiative forcing at the top of the atmosphere of over 10 Wm^{-2} over the Amazon region (Fig. 4c,d), due to increased absorption of outgoing long-wave radiation by the airborne dust.

2.3. *Other drivers of climate change in addition to radiative forcing by greenhouse gases and aerosols*

2.3.1. Anthropogenic land cover change. As well as changing in response to climate change, land cover is being modified directly by human activities. Since such modification is a direct consequence of human action and not a result of climate change, its effects on climate are a forcing as opposed to a feedback. From a global perspective, the dominant aspect of historical land cover change has been deforestation in temperate regions, and a number of modelling studies (e.g. Betts, 2001; Govindasamy et al., 2001; Myhre and Myhre, 2003) have suggested that this has exerted a radiative forcing which is most likely negative (i.e. a cooling effect) as a result of increased surface albedo especially in winter and spring when snow is lying. Most estimates of the global mean radiative forcing relative to the pre-industrial state are in the region of -0.2 Wm^{-2} + -0.3 Wm^{-2}. This global forcing is small in comparison to the positive radiative forcing of approximately 3 Wm^{-2} estimated to arise from increased GHG concentrations, but it should be noted that the forcing due to GHGs is spread relatively evenly across the globe whereas that due to anthropogenic surface albedo change is concentrated in temperate agricultural regions. Regional radiative forcings due to anthropogenic surface albedo change are estimated to be -5 Wm^{-2} or greater, leading to a regional cooling of 1–2 K

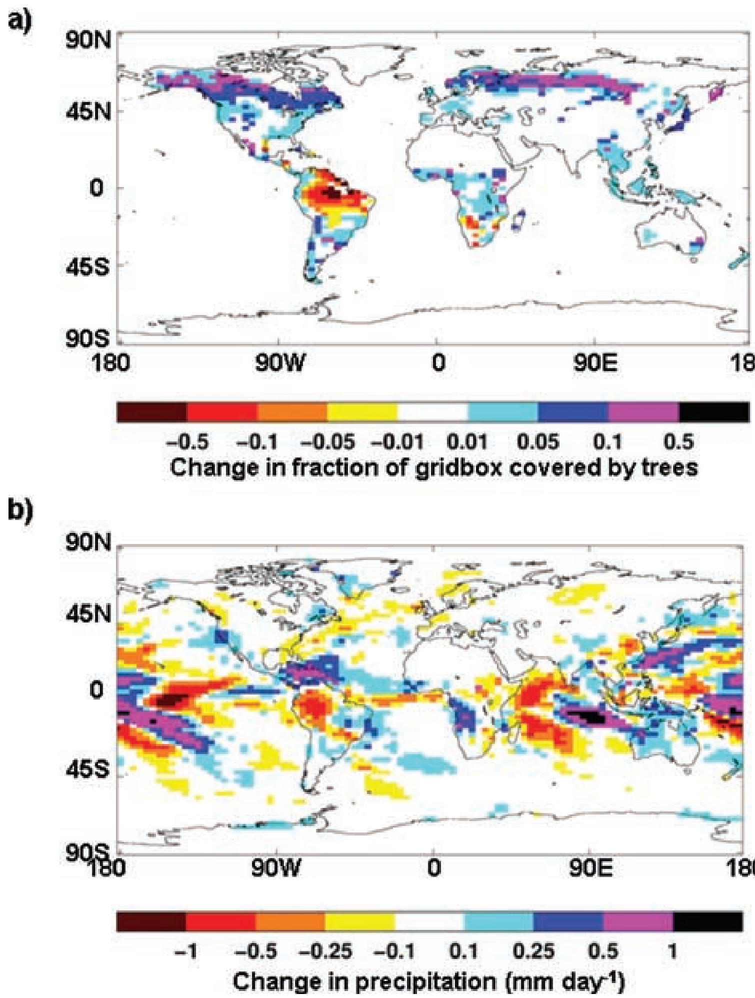

Fig. 3. (a) Changes in fractional cover of the broadleaf tree functional type relative to 2000 simulated by HadCM3LC. 30-yr mean centred around 2080. (b) Effect of biogeophysical feedback on global precipitation patterns in HadCM3LC. Difference in precipitation (mm d^{-1}) between simulations with and without biophysical feedbacks. 30-year mean centred around 2080. Figure reproduced from Betts et al. (2004), British Crown Copyright.

in the absence of any other influences on climate. This implies that the climate warming observed in these regions over the last 150 years may be smaller than that which would have occurred as a result of increased GHG concentrations alone, with the GHG warming having been partly offset by anthropogenic land cover change in a similar manner to that associated with increased aerosol concentrations.

Land cover change can also modify the surface energy budget through changes in the fluxes of latent and sensible heat. While such processes will act as anthropogenic perturbations to the climate system, they do not involve direct perturbations to the Earth's radiation budget and therefore cannot be considered to be radiative forcing. The term 'non-radiative forcing' has been proposed (Jacob et al., 2005), but this cannot be quantified in terms comparable with radiative forcing, so at the present time, the effects of these processes may be best discussed in terms of temperature changes. Model results suggest that the combined effects of past tropical deforestation may have exerted regional warmings of approximately 0.2 K. Such changes may also have perturbed the global atmospheric circulation affecting on regional climates remote from the land cover change (Chase et al., 2000; Zhao et al., 2001; Pielke Sr. et al., 2002).

Many scenarios of future GHG emissions include contributions from land cover change, but the biogeophysical effects of such changes are not usually included as inputs to climate models. Feddema et al. (2005) examined the importance of land cover changes implied by two of the IPCC SRES emissions scenarios (Nakićenović et al., 2000), by using the using the National Center for Atmospheric Research (NCAR) GCM to simulate change changes induced by changes in the physical properties of the land surface due to land cover changes projected by the IMAGE model (Alcamo et al., 1998) (Fig. 5). These simulations suggested that the effects on regional climate change are significant in comparison with those of GHG-induced climate change. For example, the SRES B1 scenario implies reforestation in mid-latitudes and relatively little tropical deforestation, whereas the A2 scenario implies less mid-latitude reforestation but extensive tropical deforestation (Fig. 5). These differences in projected land cover lead to significant variations in the predicted climate change at regional

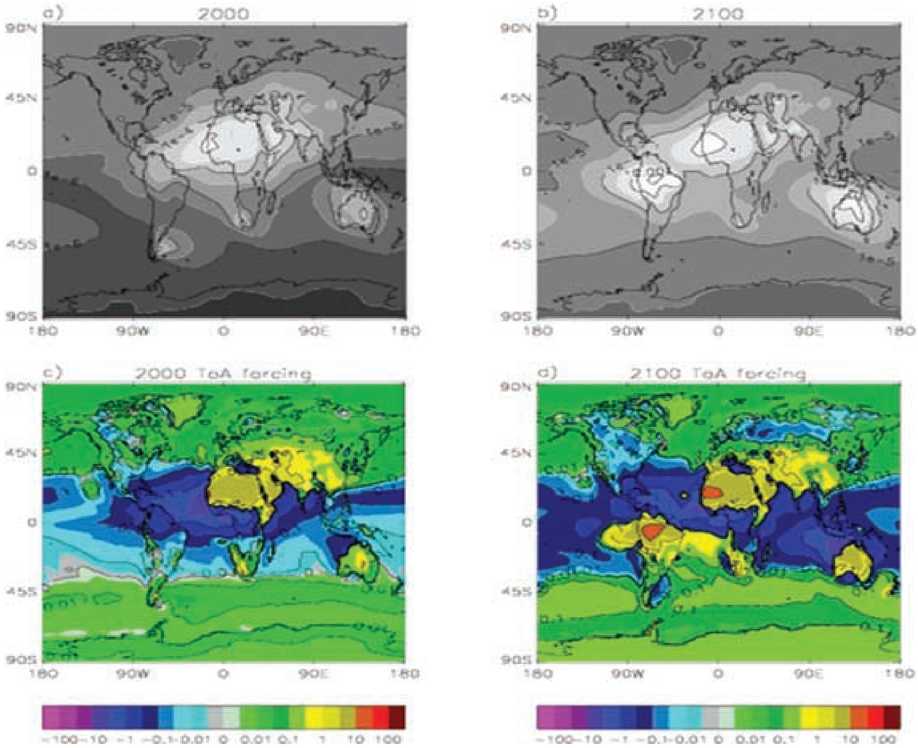

Fig. 4. (a) Atmospheric dust concentrations simulated with present-day climate and vegetation cover in the HadAM3 GCM (b) Atmospheric dust concentrations simulated with 2100 climate and vegetation cover (c) Simulated top-of-atmosphere (ToA) radiative forcing at present-day resulting from dust concentrations in (a). (d) ToA radiative forcing at 2100 resulting from dust concentrations in (b). Figure reproduced from Woodward et al. (2005), British Crown Copyright.

scales. For example, the extensive deforestation of Amazonia by 2100 in the A2 scenario (Fig. 5) leads to a warming of that region of approximately 2 K due to a reduction in evapotranspiration (Fig. 6). This warming would occur in addition to the warming due to increased greenhouse gas concentrations.

Feedbacks from the oceans may enhance the effects of land cover change on climate. For example, Delire et al. (2001) found that in the Indonesian Archipelago, the impacts of deforestation on simulated wind speeds may be sufficient to modify ocean up-welling and cause warming over the surrounding ocean surfaces, in addition to the warming caused over land by reduced evaporation. This amplified warming may impact global-scale atmospheric circulations.

Irrigation can also increase the surface moisture flux and hence reduce the Bowen ratio, exerting a cooling influence on local near-surface temperatures. Boucher et al. (2004) introduced present-day patterns of irrigation into the Laboratoire de Meteorologie Dynamique (LMD) GCM and found a simulated surface cooling of up to 0.8 K in some regions (Fig. 7).

Plans and strategies for adaptation to climate change require specific, local detail of climate change. Although this can be provided by regional climate models, these are typically only used for down-scaling of radiatively-forced global climate change. Climate change adaptation plans may therefore be inappropriate if based on projections that ignore land use change.

2.3.2. Urban heat islands and anthropogenic heat release.. Built-up areas exert significant influences on their local climates, with an ‘urban heat island’ being observed in many cities. This is due partly to the influence of the urbanized landscape on the surface energy budget and local meteorology, and partly from sources of heat arising from human activities (‘Human Energy Production’, HEP). The nature of the land surface is a key factor influencing the sensitivity of near-surface climates to radiative forcing by increasing greenhouse gas concentrations, so the responses of urban climates to radiative forcing may be different to those of non-urban climates. Moreover, increases in anthropogenic heat sources may exert an additional direct forcing of local climates. The global total HEP heat flux is estimated as 0.03 Wm^{-2} (Nakicenovic, 1998). If this energy release were concentrated in cities, which are estimated to cover 0.046% of the Earth’s surface (Loveland et al., 2000) the mean local heat flux in a city would be 54 Wm^{-2}. Daytime values in central Tokyo typically exceed 400 Wm^{-2} with a maximum of 1590 Wm^{-2} in winter (Ichinose et al., 1999). Although HEP is a very small influence at the global scale, it may be important for local climate changes in cities (Crutzen, 2004).

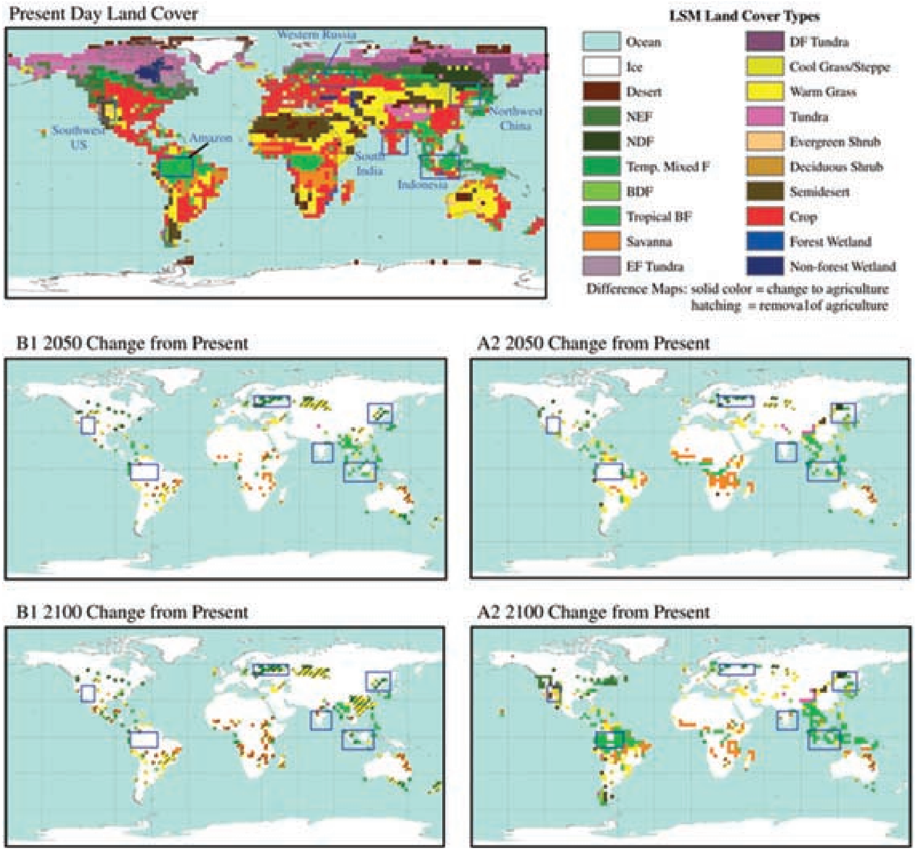

Fig. 5. Present-day land cover (top panel) and changes in land cover due to land use change consistent with the B1 and A2 SRES scenarios. Figure reproduced from Feddema et al., 2005), copyright Science magazine.

Betts and Best (2004) included an urban heat island parametrizetion into a GCM and examined the effects of a tripling of the global anthropogenic heat release which could plausibly be estimated to occur at approximately the same time as a doubling of CO_2. Although there was no discernible effect on global mean temperatures, the additional warming effect of the tripled heat source on minimum temperatures in cities was approximately 50% of that due to doubling CO_2. This suggests that plausible increases in anthropogenic heat release could exert a significant additional influence on urban climates, with particular implications for impacts on human health through unrelieved heat stress overnight.

Scenarios of climate change do not consider the influences of urban areas on their own local climates. Consequently, it may not be appropriate to apply such scenarios to climate change impacts studies in the context of built-up areas. While this problem may be partially addressed by combining climate change scenarios with representations of present-day urban heat islands, this will not address the interactions between urban landscapes and radiative forcing nor account for increasing anthropogenic heat sources. These processes can only be accounted for by the inclusion of urban meteorological processes and anthropogenic heat release within climate models.

2.3.3. Physiological forcing of climate by the direct effect of increased CO_2 concentrations on plants.. As well as exerting a radiative forcing of the climate system, increasing concentration of atmospheric CO_2 also perturb the climate system through direct effects on plant physiology. Plant stomatal apertures typically open less widely under higher CO_2 concentrations (Field et al., 1995), which directly reduces the flux of moisture from the surface to the atmosphere through transpiration (Sellers et al., 1996). A decrease in moisture flux modifies the surface energy balance, increasing the ratio of sensible heat flux to latent heat flux and therefore warming the air near the surface (Sellers et al., 1996; Betts et al., 1997). Increased photosynthesis as a result of higher CO_2 concentrations ('CO_2 fertilization') can lead to increased leaf area and changes in vegetation structure; this can partly offset the effects of stomatal closure at the large scale, and exert other effects, such as changes in surface albedo (Betts et al., 1997). The term 'physiological forcing' can be applied to these mechanisms (Betts et al., 2001). They can be considered to be non-radiative forcings of climate change, as distinct from a climate feedback, since the mechanisms involve direct responses to CO_2 rise and not a response to climate change. Physiological forcing of changes in the surface moisture budget is not quantifiable in terms of a Wm^{-2} radiative forcing.

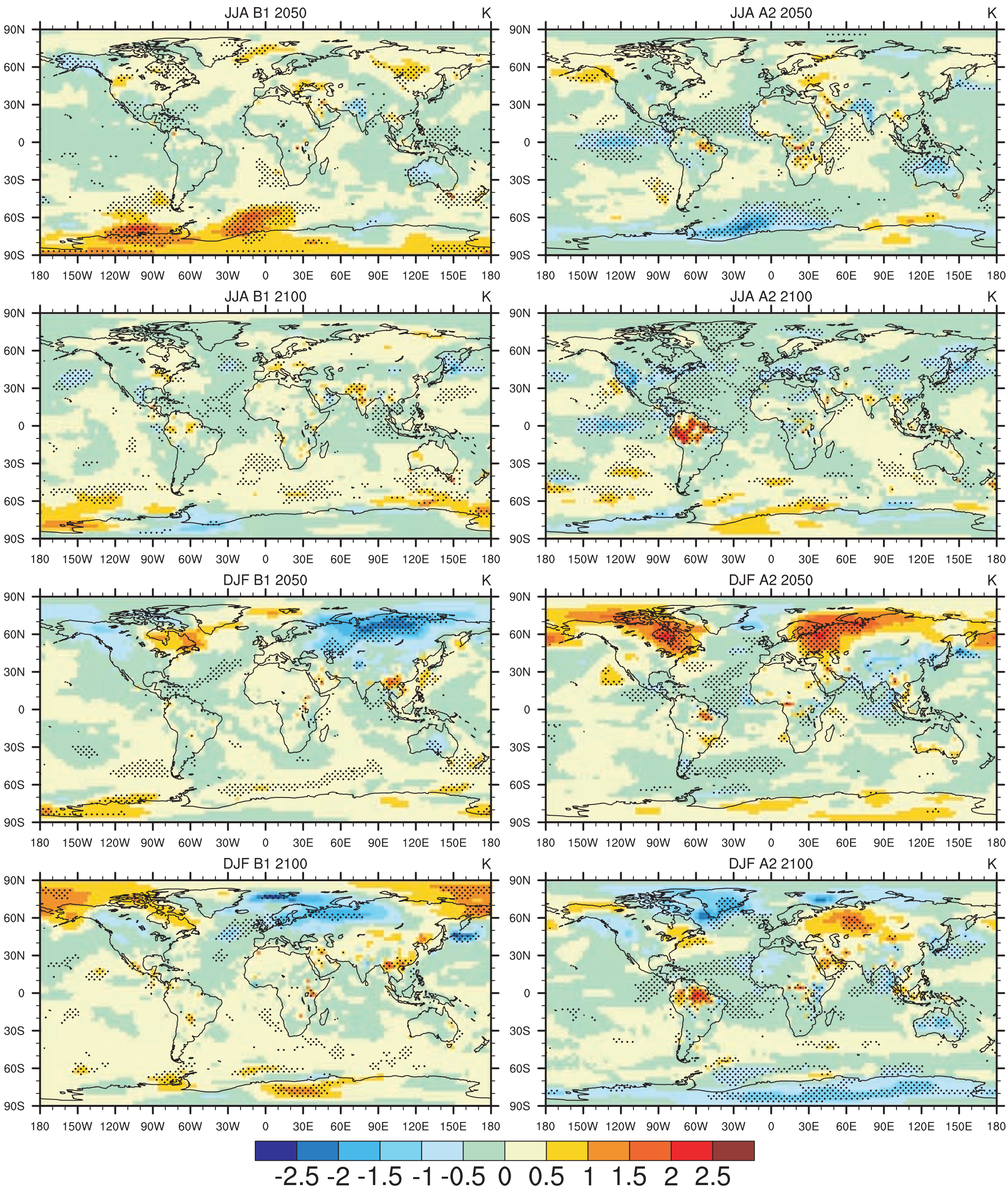

Fig. 6. Changes in surface temperature (K) relative to 2000 due to the biophysical effects of land cover change (albedo, moisture availability, aerodynamic roughness); 2050 June–July–August (JJA) (top row); 2100 JJA (2nd row); 2050 December–January–February(DJF) (3rd row); 2100 DJF (4th row). SRES scenarios B1 (left column) and A2 (right column). EF: Evergreen Forest. DF: Deciduous Forest. B: Broadleaf. N: Needleleaf. F: Forest. Figure reproduced from Feddema et al. (2005), copyright Science magazine.

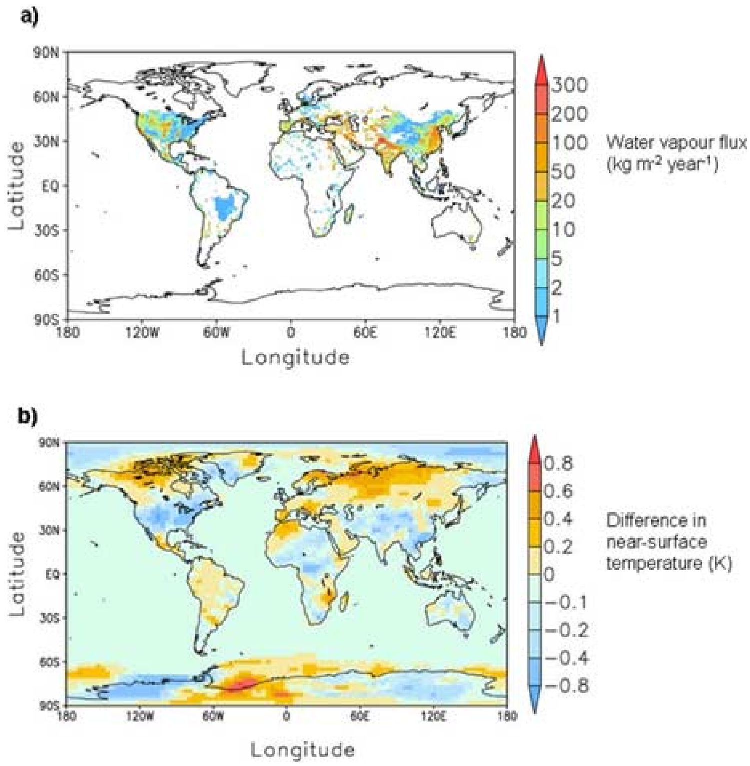

Fig. 7. (a) Present-day water vapour flux from irrigation (kg m^{-2} yr^{-1}). Data from Doll and Siebert (2000, 2002) as presented by Boucher et al (2004). (b) Effect of present-day irrigation on temperature (K) in the LMD GCM: Difference between simulations with and without irrigation. Figure reproduced from Boucher et al. (2004), copyright Springer-Verlag.

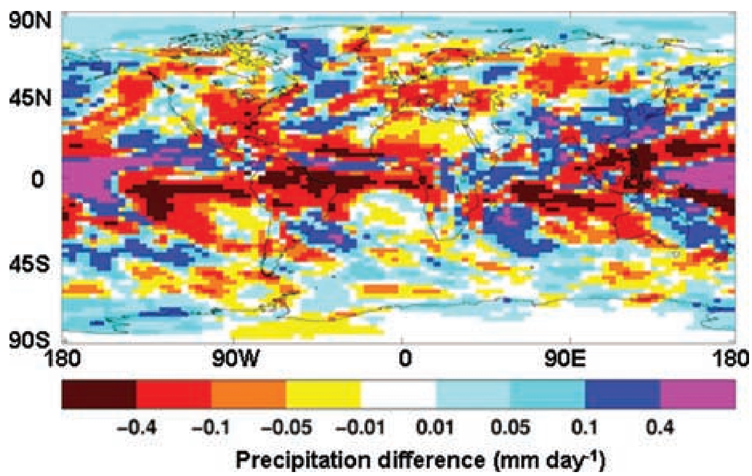

Fig. 8. Effect of physiological forcing (reduced stomatal opening under higher CO_2) on global precipitation patterns (mm d^{-1}). Difference between simulations with stomata experiencing CO_2 projected for the 2080s (IS92a scenario) and present-day CO_2. Both simulations are subject to CO_2-induced radiative forcing projected for the 2080s. Figure reproduced from Betts et al. (2004), British Crown Copyright.

Climate modelling studies suggest that doubling CO_2 would lead to a warming of 0.4 K–0.7 K over land due to CO_2-induced stomatal closure (Sellers et al., 1996; Betts et al., 1997; Cox et al., 1999), including the effects of both reduced transpiration and decreased water vapour concentrations. With CO_2 having risen by approximately 35% relative to pre-industrial, this may suggest that this process may have contributed 0.1 K–0.2 K to the observed historical temperature rise over land.

A decrease in transpiration also implies a decreased return of moisture to the atmosphere for precipitation. In regions such as Amazonia where a large proportion of water for precipitation is supplied by evaporation from the land surface rather than advection from over the oceans (Salati and Vose, 1984), reduced transpiration by stomatal closure could lead to reduced precipitation. Betts et al. (2004) examined the possible effect of this in Amazonia, using a coupled climate-biosphere model. Two simulations were performed, both with increasing radiative forcing from CO_2 rise according to the IS92a scenario, but with only one simulation including physiological forcing of stomatal closure and CO_2 fertilization.

The two simulations showed marked differences in precipitation in many regions across the globe by the end of the 21st century (Fig. 8). Over Amazonia, for example, the simulation with physiological forcing featured a more drastic decrease in precipitation. In Western Amazonia this was due to a reduced evaporative return of water to the atmosphere through reduced canopy conductance (Cox et al., 1999).

However, there were also large-scale patterns of precipitation increase and decrease across the globe, indicative of differences in the global atmospheric circulation. These are attributable to different rates of land surface warming in the two simulations as described above. In the simulation including physiological forcing, the generally lower rate of transpiration leads to greater warming over land (Sellers et al., 1996, Betts et al., 1997, Cox et al., 1999). Since the Northern Hemisphere includes more land than the Southern Hemisphere, a greater rate of warming over land leads to an inter-hemispheric difference in warming which would be expected to modify global atmospheric circulation. In particular, the Inter-Tropical Convergence Zone (ITCZ), an area of ascending air motion and hence precipitation, is drawn northwards by a warmer Northern Hemisphere. This changed the patterns of precipitation around the equator, bringing more rainfall to some regions but less to others.

Physiological forcing may therefore exert some complex influences on regional climate change, which should be accounted for along with the global influences of radiative forcing.

2.4. *The direct forcing of ecosystem impacts by changes in atmospheric composition: CO_2 fertilization and O_3 poisoning*

Projections of the direct effects of rising CO_2 on vegetation are generally made using models incorporating mechanistic descriptions of plant physiological processes, based on individual-level observational and experimental studies. In particular, photosynthesis is generally observed to increase with rising CO_2, but the rate of this increase reduces with rising CO_2, implying a saturation of photosynthesis at high CO_2. Pot and plot-scale studies also indicate an increased efficiency of water use due to the reduced opening of stomata under higher CO_2. Biogeography models and DGVMs generally adopt some methodology for scaling up of these processes to generate projections at large scales.

Model simulations of global vegetation responses to increasing CO_2 (neglecting any associated climate change) show an increase in net primary productivity (NPP) and carbon storage. Cramer et al. (2001) simulated global mean NPP and carbon stocks to nearly double by 2100 when CO_2 effects were included without climate change. These simulations also featured some changes in global vegetation distribution, mainly due to increased water-use efficiency allowing more growth in semi-arid regions. The African and South American equatorial forests expanded into savanna regions, and the relative viability of woody vegetation also increased in India. Australia became more grass-covered, and the boundary between the Sahara desert and the Sahel moved northwards.

The radiative and physiological forcings exerted by CO_2 rise may exert non-additive impacts on ecosystems. Haxeltine (1996) found that climate warming alone increased NPP by 6%, largely as a result of a net expansion of woody vegetation under climate change. The effect of CO_2 fertilization was to increase NPP by 30% in the absence of any forest expansion, but when climatically-induced forest expansion was considered, the overall increase in NPP was 43%. This suggests that the effects of climate change of biogeography may be a key factor in limiting NPP responses to increased CO_2 concentrations.

Cramer et al. (2001) found CO_2 fertilization and climate change to interact non-linearly in DGVMs. By 2100, climate change alone generally led to a negative net atmosphere-land carbon flux or net ecosystem productivity (NEP) which is the difference between NPP and soil respiration. However, CO_2 increase alone led to positive NEP. The linear sum of these effects was a general increase in NEP, but in simulations driven by both CO_2 and climate change together, negative NEP was simulated in many parts of the tropics.

Betts et al. (2004) found the simulated dieback of Amazonian forest under a drying climate to be reduced but not eliminated by CO_2 fertilization. This was despite the further reduction in local precipitation induced by stomatal closure. Physiological forcing therefore enhanced the drying of the climate but slowed the forest dieback due to the increased water use efficiency.

Another atmospheric constituent that directly affects plant productivity is ozone (O_3). Excessive O_3 concentrations can damage plant cells and therefore reduce productivity, with the risk of decreasing crop yield (McKee and Long, 2001; Morgan et al., 2003; Morgan et al., 2004). As an illustration of this, Sitch et al. (2005) used an offline vegetation model driven by changes in climate, CO_2 and O_3 consistent with the IS92a emissions scenario, and compared the terrestrial carbon storage in simulations with and without O_3 physiological effects. O_3 concentrations were projected to increase by 10%–20% over the most populated parts of the temperate and tropical regions, and this was simulated to reduce terrestrial carbon storage by up to 4 kg C m^{-2} in the Eastern USA, Europe, north and south-east Asia and the tropics, a reduction of approximately 25%. When O_3 effects were investigated with and without CO_2 effects, it was found that O_3 damage was reduced under higher CO_2 concentrations as a result of CO_2-induced stomatal closure reducing the flux of O_3 into stomatal cavities.

2.5. *Interactions between impacts*

The impacts of climate change, such as on ecosystems and hydrology, are generally studied in isolation from each other. However, these impacts areas may interact strongly with each other. For example, the impacts of CO_2 rise and climate change on ecosystems may affect the surface moisture budget and hence modify the impacts of climate change on soil moisture and runoff. A reduction in transpiration due to plant stomatal closure under

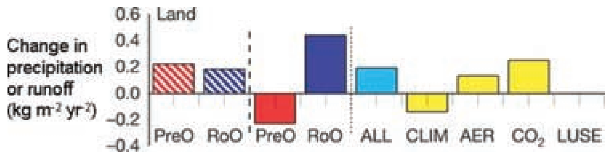

Fig. 9. Attribution of observed runoff changes to CO_2 physiological forcing. Observed precipitation ('PreO'; red bars) and runoff ('RoO'; dark blue bars), and modelled runoff with all mechanisms (ALL; light blue bar) and individual components (CLIM, AER, CO_2 and LUSE; yellow bars). Units are kg m^{-2} yr^{-2}. Lined bars refer to trends over 20^{th} Century and solid bars to post-1960 trends. Figure reproduced from Gedney et al. (2006), British Crown Copyright.

increased CO_2 implies an increase in moisture remaining in the soil and hence more water available for drainage into rivers.

Gedney et al. (2006) used established detection and attribution techniques to assess the contributions of climate change and variability, CO_2 physiological forcing, land use change and solar dimming. Gedney et al. (2006) used the 2nd Met Office Surface Exchange Scheme (MOSES2) (Essery et al., 2003), which is a coupled ecosystem-hydrology model with mechanistic representations of plant physiology with a close coupling between photosynthesis and transpiration including responses to CO_2 concentration, soil moisture, temperature, humidity and photosynthetically-active radiation (Collatz et al., 1991, 1992; Sellers et al., 1992; Jacobs, 1994; Cox et al., 1999). The model was driven by different combinations of observational climate data and measured CO_2 concentrations, reconstructed land use change (Klein Goldewijk, 2001) and changes in short-wave radiation simulated by the HadGEM1 climate model, and compared with observationally-based continental-scale river flow records (Labat et al., 2004) (Fig. 9). Using optimal fingerprinting techniques (Tett et al., 2002), Gedney et al. (2006) found that suppression of transpiration by CO_2 physiological forcing was detectable in the historical records. The historical records were found to be inconsistent with alternative explanations that exclude CO_2 physiological forcing. Gedney et al. (2006) found that the observed 3% rise in global river flow over the 20th century is attributable to CO_2 physiological forcing enhancing river flows by 5% with a 2% offset by climate change. This implies that the annual global land-atmosphere moisture flux has decreased by approximately 60 000 tonnes of water per second due to physiological forcing.

Most projections of the impacts of CO_2-induced climate change on hydrology neglect the direct effect of increased CO_2 concentrations on vegetation and the consequent effects on the surface moisture balance (Arnell et al., 2001). The results of Gedney et al. (2006) imply that this may result in incomplete assessments of the consequences of the anthropogenic CO_2 rise for water resources. Complete assessments of hydrological impacts will also require the interactions with ecosystem impacts to be considered.

3. Informing climate change mitigation

3.1. Unintended consequences of carbon sequestration

Since forest growth sequesters carbon dioxide from the atmosphere, this is one means proposed for slowing the rise in atmospheric CO_2 in order to mitigate climate change (UNFCCC, 1997). Under the terms of the Kyoto Protocol, sequestration by carbon sink plantations may be counted against emissions in calculating a party's emissions budget. However, since changes in forest cover also exert other radiative forcings, particularly through surface albedo change, it should be noted that carbon accounting may not give a true reflection of the impact of forest cover changes on the total radiative forcing of the climate system.

Betts (2000) considered cases of afforestation and reforestation over 1 ha plots at points north of 45 °N, and estimated the radiative forcing due to surface albedo change and carbon sequestration for each plot. In milder regions with minimal seasonal snow cover and vigorous forest growth, the surface surface albedo decrease was relatively small in the annual mean, while carbon sequestration was estimated to be large, so the negative forcing due to carbon sequestration was larger than the positive forcing due to decreased surface albedo. The net forcing was therefore negative, but smaller than that expected due to carbon sequestration alone. In colder regions, however, the simulated annual mean surface albedo change was large, while the estimated carbon sequestration was relatively small, so the overall radiative forcing due to forestation was positive (Fig. 10). These model results suggest that the overall contribution of a forest plantation to mitigating radiatively-forced climate change could be smaller than that expected on the basis of carbon accounting, or could even be opposite to that intended. Afforestation and reforestation in cold regions could therefore provide a less effective means of climate change mitigation than previously anticipated, or could even act as an unintentional means of exacerbating climate warming.

Schaeffer et al. (2006) suggested that the use of biofuel may exert a double effect on reducing temperature rise by mitigating CO_2 emissions, while also maintaining a relatively high surface albedo. Biofuel crops tend to be short in stature and hold less foliage than forests, so consequently the surface albedo of an area of biofuel plantations is higher than a forested landscape.

In contrast, since tropical deforestation exerts a warming effect through reduced evapotranspiration (Fig. 6), it follows that reforestation (or avoided deforestation) in tropical regions could exert a double cooling effect through carbon sequestration and increased evaporation and cloud cover.

Jackson et al. (2005) showed that water resources are directly impacted by forestry activities designed for carbon sequestration. With carbon offsets through forestry being an expanding tool for climate change mitigation, these studies make crucial contributions.

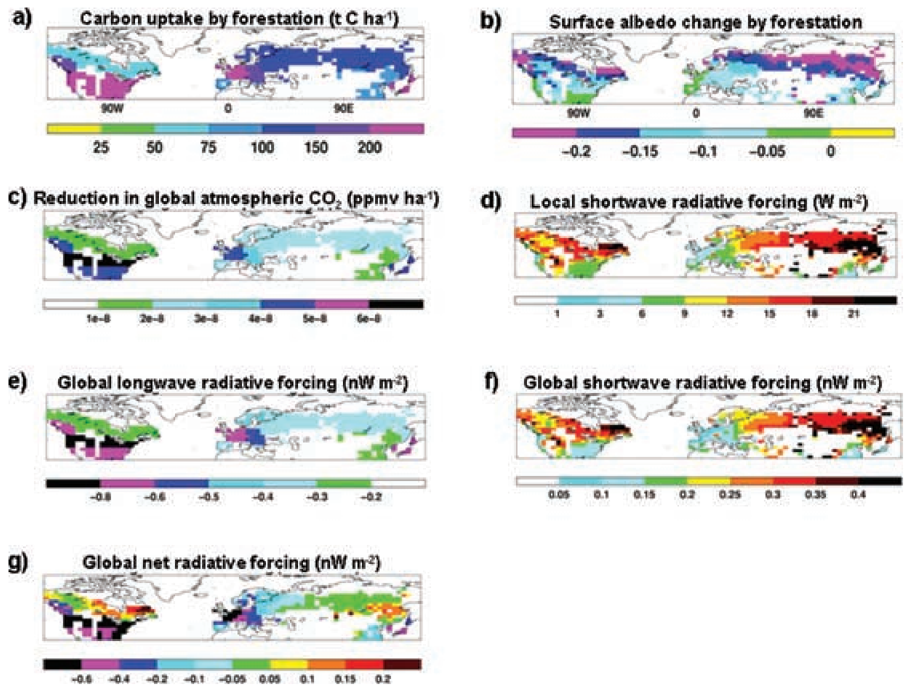

Fig. 10. Comparison of radiative forcings exerted by forest plantations through carbon sequestration and surface albedo change, estimated with carbon uptake data from the literature and model simulations of surface albedo and radiative forcing (Betts, 2000). (a) Carbon uptake by 1ha plantations over 1 harvest rotation period, including above- and below-ground carbon. (c) Resulting changes in atmospheric CO_2 concentration for 1 ha plantations in the different locations. (d) Global long-wave radiative forcing due to changes in CO_2 concentration; negative numbers imply a reduction in the greenhouse effect. (b) Simulated change in annual mean surface albedo due to forest plantations. (d) Resulting change in local short-wave radiative forcing. (f) Global mean short-wave radiative forcing arising from local forcing in (d) at each location. (g) Global net radiative forcing (shortwave+longwave), the sum of panels (e) and (f). Yellow, red and orange indicate a net warming effect (reduced surface albedo exerting a positive short-wave radiative forcing which is larger than the negative long-wave radiative forcing arising from carbon sequestration).

3.2. The 'CO_2 equivalent' problem

Current metrics of the climatic effects of different GHGs assume that radiative forcing and global mean surface temperature are appropriate quantities through which to compare human influence on climate. The concept of a 'CO_2 equivalent' concentration of non-CO_2 GHGs based on their global warming potentials (GWPs) is often used, representing long-term average radiative forcing. However, most concern over climate change focuses on impacts, and recent work shows that human activities affect these impacts through processes other than the radiative forcing by GHG. Therefore, current metrics may not be appropriate.

The discovery by Gedney et al. (2006) that the physiological effects of CO_2 on runoff may be comparable with those of climate change raises questions over the general applicability of current 'CO_2 equivalent' metrics. With CO_2 exerting additional impacts by-passing the radiative forcing pathway, comparison with other GHGs in terms of GWPs alone may be not appropriate. The use of radiative forcing alone to quantify relative impacts of forcing agents on areas relating to ecology or hydrology should therefore be treated with caution. If the interest is in these impacts rather than global mean temperature, the use of alternative metrics may be appropriate.

Also, if the source of CO_2 is from land cover change then the CO_2-equivalent of biophysical land surface changes needs to be considered. Betts (2000) made preliminary calculations similar to a 'CO_2-equivalent' of albedo change using radiative forcing. Betts (2000) introduced the concept of 'Emissions Equivalent of Shortwave Forcing' (EESF) to express a particular change in surface albedo in terms of the carbon emissions which would exert the same global mean radiative forcing (Table 1). Since the change in surface albedo (and hence change in short-wave radiative forcing) arising from a particular change in forest cover depends on the underlying surface albedo, the EESF of forestation shows very large geographical variation.

The CO_2 equivalent of non-radiative forcings, and of direct impacts, such as on changes in runoff have not yet been examined.

4. Conclusions

The interactions between land ecosystems and the atmosphere have major implications for strategies for adaptation to anthropogenic climate change and the mitigation of its causes. Adaptation strategies require robust assessments of future

Table 1. Sequestration and albedo forcings in terms of carbon stock change

Region	Sequestration potential	Emissions-equivalent of short-wave forcing	Net equivalent stock change	NESC/SP
	[SP] (t C ha^{-1})	[EESF] (t C ha^{-1})	[NESC] (t C ha^{-1})	(%)
Boreal				
Former Soviet Union	80 to 120	100	−20 to 20	−30 to 20
British Columbia	190	80	110	60
Rest of Canada	60	90	−30	−50
Nordic Europe	120	60	60	50
Temperate				
Western Europe	140 to 280	30	110–250	80– 90
Eastern Europe	150	40	110	70
Southern Europe	90	40	50	60
Temperate USA	200 to 420	70	130–350	70–80
Southern USA	210	40	170	80
China	80	60	20	30
Rest of Temperate Asia	200	60	140	70

Column 2 gives ranges of regional estimates of carbon sequestration potential by forestation over 1 rotation period, based on literature data. Plantations are assumed to be coniferous. Sequestration potentials include above- and below-ground biomass. In Column 4, NESC = SP - EESF. Data are rounded to the nearest 10 to avoid misleading precision. After Betts (2000).

climate change and its impacts at global and regional scales, and these depend on biogeochemical and biogeophysical ecosystem feedbacks on radiatively-forced climate change and also additional anthropogenic forcings through land cover change and plant physiological responses to changes in CO_2 concentration. Changes in atmospheric composition can also directly affect ecosystem impacts, with knock-on effects on other impacts, such as hydrology.

A general implication of these issues is that adaptation strategies should regard existing projections of climate change impacts as preliminary. Account should be taken of the fact that most climate research has focussed on assessing whether anthropogenic radiatively-forced climate change may be serious enough to warrant action, which arguably has a relatively low requirement for regional detail and process representation. However, adaptation plans require a more complete picture of radiatively-forced climate change in the context of other aspects of global change, and more precise information on individual locations.

Any adaptation strategy or decision, which is sensitive to the rate of climate change, will be influenced by consideration of feedbacks on global climate change through the carbon cycle (and other biogeochemical cycles). Strategies or decisions based on climate scenarios which do not take these feedbacks into account may not allow for a sufficiently rapid response or rate of adaptation; for example, increases in the frequency of extreme weather events may occur more rapidly than previously expected, so there may be a more urgent need to 'future-proof' new infrastructure and put in place measures to deal with humanitarian crises in vulnerable regions.

Strategies relating to land use, agriculture and water availability will require regional climate change scenarios which consider the effects of land use change and biological processes on climate, and will need to consider climate impacts acting in synergy with each other and with changes in atmospheric composition. These issues will be important for future assessments of food security, food supply, health risks and migration pressures by national governments, international bodies, such as the World Health Organisation and Food and Agriculture Organisation, and bodies responsible for dealing with humanitarian crises (such as Aid organisations and Armed Forces).

At city scales, issues relating to building design, urban planning and health service provision will need to consider the localized effects of urban heat islands in addition to larger-scale climate change. This will affect strategic decision making by local authorities and other local organizations and individuals, in addition to national and international bodies responsible for aspects of urban development.

Mitigation strategies, which involve land cover change, such as plantations for carbon sequestration or biofuels, may exert additional effects on climate change and its impacts. Merely accounting for the net reduction in carbon emissions may not provide an accurate measure of the full effect of these strategies for mitigating climate change. Therefore, if the aim of land management in the context of the UNFCCC is to reduce climate warming, the full effects of changes in land cover should be considered.

Mitigation decisions, which rely on the comparison of the effects of different GHGs, should take account of the other climatic effects of these climate change drivers which do not act through the enhanced greenhouse effect. Some gases exert physiological effects on plant life (and hence on the water cycle) while others do not, so the current concept of 'CO_2 equivalent' based on radiative forcing does not provide a true comparison of the impacts of different GHGs on the climate system. If mitigation policies require a prioritization of actions based on the relative impacts of different GHGs and other forcing agents, the full range of effects of these agents should be considered and the 'CO_2 equivalent' concept should be revised to include non-radiative forcings.

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