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Review

The role of interactions in a world implementing adaptation and mitigation solutions to climate change

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The papers in this volume discuss projections of climate change impacts upon humans and ecosystems under a global mean temperature rise of 4°C above preindustrial levels. Like most studies, they are mainly single-sector or single-region-based assessments. Even the multi-sector or multi-region approaches generally consider impacts in sectors and regions independently, ignoring interactions. Extreme weather and adaptation processes are often poorly represented and losses of ecosystem services induced by climate change or human adaptation are generally omitted. This paper addresses this gap by reviewing some potential interactions in a 4°C world, and also makes a comparison with a 2°C world. In a 4°C world, major shifts in agricultural land use and increased drought are projected, and an increased human population might increasingly be concentrated in areas remaining wet enough for economic prosperity. Ecosystem services that enable prosperity would be declining, with carbon cycle feedbacks and fire causing forest losses. There is an urgent need for integrated assessments considering the synergy of impacts and limits to adaptation in multiple sectors and regions in a 4°C world. By contrast, a 2°C world is projected to experience about one-half of the climate change impacts, with concomitantly smaller challenges for adaptation. Ecosystem services, including the carbon sink provided by the Earth's forests, would be expected to be largely preserved, with much less potential for interaction processes to increase challenges to adaptation. However, demands for land and water for biofuel cropping could reduce the availability of these resources for agricultural and natural systems. Hence, a whole system approach to mitigation and adaptation, considering interactions, potential human and species migration, allocation of land and water resources and ecosystem services, will be important in either a 2°C or a 4°C world.

Keywords: climate change; integrated assessment modelling; adaptation; extreme weather events; ecosystem services; biodiversity

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1. Introduction

The projections of climate change impacts under a 4°C mean global temperature rise contained in this volume, like most other assessments of future climate change impacts, generally consider impacts in each sector and region independently. Such projections often consider a set (or sets) of future socioeconomic futures, some of which may include a level of mitigation action. This is useful to indicate the levels of impacts that might occur, with and without mitigation, but the utility of such projections would be greatly improved by increased consideration of the interactions between sectoral and regional processes, including human adaptation to climate change impacts, as well as mitigation actions. Such interactions may have profound consequences for the future wellbeing of human and natural capital, particularly for global temperature rises as large as 4°C (relative to preindustrial levels). Many of these interactions are currently not considered, or not well integrated, into quantitative estimations of potential consequences of climate change, or of benefits of mitigation action. This is especially true given the potentially important feedback processes in the Earth system becoming evident through observations, yet not currently adequately simulated by global circulation models (GCMs). Such feedbacks could greatly exacerbate impacts for a given greenhouse gas emission scenario beyond those estimated by models.

This review provides a brief summary of some climate change impact estimates from this volume and elsewhere, comparing impacts under 4°C of global mean temperature rise (hereafter referred to as 'a 4°C world') with those under 2°C (hereafter referred to as 'a 2°C world'). It discusses prominent examples of eight types of potentially significant interactions and the degree to which they have been handled in various modelling approaches. It does not, however, provide complete coverage of all types of interactions, or of all possible interactions within each type. It notes that these processes might be excluded from modelling exercises because of an inability to quantify the strength of the interaction, and also because of ignorance of the importance of interactions between disparate disciplines. It also suggests potential ways forward in modelling these interactions.

The types of interactions considered are:

- climate change-induced impacts in one sector affecting other sectors in the same region;
- human adaptation to climate change-induced impacts in one sector affecting other sectors in the same region;
- climate change impacts in one region having consequences for other regions;
- climate change mitigation and adaptation involving changes in land use, which then interacts in a complex fashion with climate change and its impacts;
- impacts in different sectors coincident in the same region having disastrous consequences therein;
- projected increases in extreme weather events exacerbating climate change impacts;
- interactions within sectors that are not combined in analyses; and
- feedback processes that could exacerbate climate change impacts.

Table 1. Typology of IAMs focusing on their potential for representation of interactions between climate change impacts in various sectors, and between climate change impacts and mitigation/adaptation processes.

potential to represent interactions	none	low	high
question to which typically applied/ for which designed	cost–benefit analysis	scenario analysis or tolerable windows approach	scenario analysis
representation of climate change impacts	simple, either global (PAGE) or regional; sectoral detail only in FUND	look-up tables based on process-based model output	process based
representation of global economy	detailed	detailed	detailed
examples	FUND, PAGE, MERGE, DICE/RICE	ICLIPS, AIM	IMAGE, CIAS, GCAM

There are thousands of studies examining impacts on a single sector within a single region with no interactions. When considering impacts holistically at a global scale, Parry [1] provides one of the first studies providing a consistent assessment across global regions and sectors. This study used the full consistent set of SRES emissions scenarios [2], consistent downscaled climate scenarios and up-to-date climate and impact models.

Integrated assessment models (IAMs) were developed to encompass an interdisciplinary approach to the study of climate change and climate change policy. Goodess *et al.* [3] provide a full review and categorization of these models. A brief summary of the types of models is given here (table 1).

Biophysically based IAMs such as IMAGE, AIM, ICLIPS, GCAM and CLIMPACTS ([3] and references therein) variously examine sectors and/or regions of the world, spanning multiple disciplines, and thus theoretically allowing models to capture interactions between sectors. However, few have yet exploited their full potential to study interactions. Hence, table 1 refers to the *potential* for IAMs to represent interactions, rather than whether they actually do, or have done so. Representation of impacts varies significantly between these frameworks. In the case of IMAGE, they are detailed and include interactions such as carbon cycle-induced terrestrial vegetation die-back owing to climate change (leading to an accelerated rate of climate change), links between climate change, land-use change and changes to agricultural systems, and demographics [4]. In others, such as ICLIPS and AIM, look-up tables relating impacts to climate variables are used. This precludes detailed interaction between underlying impact model components. The CIAS integrated modelling framework [5] is designed to handle interactions between sectors.

Studies considering climate change impacts in a holistic fashion within or without an IA framework allow estimation of climate change impacts at a regional scale, and, in some cases, a relatively high spatial resolution. However, simple integrated models focusing on cost–benefit analysis provide only global-scale estimates. Such models typically represent climate change impacts as a combination of market and non-market economic damages, not in physical metrics [6], and do not consider the interactions listed earlier. Arguably, the most useful application of such models is in probabilistic analyses [7,8]. Such models use simple equations to detail the relationship between monetized impacts and temperature. The damage function shape used is theoretical and is often based on an arbitrary choice of function. Specifically, market damages are quadratic in DICE/RICE [9] and MERGE [10], between linear and cubic in a probabilistic fashion in PAGE, and take a variety of theoretical forms in FUND. Only FUND's damage functions take into account the rate of temperature change as well as its magnitude (in the agricultural and ecosystem sectors only). However, the representation of the climate system in some of these simple models often is not consistent [11] with that of the Intergovernmental Panel of Climate Change (IPCC) [12]; for example, FUND shows smaller temperature responses to reducing emissions than IPCC simulations, and PAGE assumes strong carbon cycle feedbacks. Modellers have updated their code to remove these inconsistencies [13,14]. While only FUND is sector-specific [7], interactions between sectors are not considered. Non-market damages are estimated through a willingness-to-pay approach, while only PAGE explicitly simulates adaptation [8]. Damage functions tend to be calibrated using studies of climate change impacts in the USA, scaled to represent impacts in other regions. In FUND, impacts cause only instantaneous damage, hence ignoring permanent loss of ecosystem services. Mastrandrea [6] discusses these issues in further detail.

Although some key insights about some interaction processes have been obtained from biophysically based IAMs (and these are highlighted in the review), only a small number of processes has so far been studied. This paper addresses this gap by considering a much wider range of potential interactions and their possible consequences.

2. Types of interactions

(*a*) *How impacts in one sector could affect another sector in the same region*

While some of the interactions between impacts in different sectors in the same location are commonly considered, others are not. Models simulating changes in crop yields generally take into account changes in precipitation and soil moisture, thus linking change in the agricultural and hydrological sectors. However, other interactions, such as the ways in which loss of ecosystem services affect human systems, are rarely considered. I attempt to divide interactions into those generally included in physically based modelling approaches and those rarely included. Table 2 summarizes the interactions discussed.

(i) *Some interactions between sectors affected by climate change that are generally covered in physically based impact models*

Hydrology has a strong interaction with agriculture through water availability. However, the relationship between (daily) precipitation and soil moisture is not constant and, therefore, hydrological processes need to be, and often are, incorporated into process-based models designed to simulate climate change impacts upon agriculture. Models such as CERESWheat [15] simulate physiological processes in plant development, growth and evapotranspiration, using detailed soil composition data to derive water availability. They underlie prominent analyses of global and regional climate change impacts on agriculture [1,16]. Other models relying on the hedonic method [17,18] assume that projected future regional precipitation and temperature may be used as proxies for agro-economical output. Here, the relationship between precipitation and soil moisture is assumed constant and hence hydrological processes are ignored [19].

Impacts on agriculture affect human health, largely through the potential for malnutrition, and hence a few studies have estimated millions at risk of hunger resulting from climate change impacts on crops [1,4,20]. Here, changes in yields produced by CERES crop models are aggregated to generate national cereal production estimates for input to a world food trade model that balances demand and supply of food according to *per capita* gross domestic product (GDP). However, most studies only provide estimates of yield reductions, without analysing changes in production or trade [21].

Changes in hydrology can also directly affect human health, through mortality (which tends to fall with rising GDP [22], water stress or loss of livelihoods), and hydrological changes are used in estimating potential future millions of people at risk of water stress [23,24]. Similarly persons at risk from fluvial and coastal flooding have been estimated using detailed spatially downscaled projections of future populations [1,25].

The impacts of sea-level rise upon coasts will interact with coastal ecosystems causing globally significant losses of coastal wetlands, saltmarsh and mangroves (e.g. [26,27]). It will also interact with the agricultural sector through inundation, with case studies illustrating effects in a number of vulnerable regions (e.g. [25,28,29]) and for the globe as a whole [30]. However, standard approaches to the simulation of agriculture impacts (e.g. [1,20]) do not include losses owing to salinization or inundation.

(ii) *Some interactions between sectors affected by climate change that are generally not included in physically based impact models*

Loss or disruption of natural ecosystems can lead to a breakdown of ecosystem functioning, leading to a loss of ecosystem services [32]. The large proportion of species is at risk of extinction from climate change (e.g. 40% of species studied in a 4°C world; table 3); together with the effects of increased extreme events, such as drought and forest losses due to fire, this means that such services are at risk. These include the water purification provided by wetlands, the purification of air provided by forests, the protection of coastal areas from storm surges by mangroves and coral reefs, the regulation of pests and disease, the recycling of waste nutrients and the removal of carbon from the atmosphere [32,33].

In the USA, at least half of the medicines used today derive from natural sources and 116 out of 158 new drugs licensed between 1998 and 2002 were derived from natural origins [34]. However, only 1 per cent of known plants have been analysed for their potential use in medicine. Animals and microbes also make vital contributions, and the exploration of the potential of marine organisms is

Table 2. A variety of examples of cross-sectoral interactions: x-axis—driving sector, which incurs climate change impacts directly; y-axis—the incumbent sector, which incurs impacts indirectly as a result of the changes in the driving sector. Each example is followed by a (y) or an (n) indicating whether the driving sector impact has been quantified at all; secondly a (y) or an (n) indicating whether the effect of the interaction upon the incumbent sector has generally been included in physically based quantitative assessments of the impacts of climate change on the incumbent sector. Indirect effects that impact upon the incumbent sector as a result of human adaptation to impacts in the driving sector are also included.

driving sector → / incumbent sector ↓	hydrology	agriculture	coasts	terrestrial ecosystems	oceans	biodiversity	human health
hydrology	*****	adaptation to impacts increasing demand for water (n, n)	—	changes in biome type affect soil moisture content and evapotranspiration rates (some y, n)	—	as for terrestrial ecosystems	—
agriculture and food	water stress reducing crop yields (y, y)	*****	farmland loss owing to sea-level rise and salinization (y, n)	loss of carbon from soils (y, n)	—	loss of pollinators (some y, n); loss of wild crop types (y, n); pests and diseases (some y, n)	—
coasts	changes in nutrient levels in estuaries (n, n)	agricultural intensification leading to increased nutrient run-off (n, n)	*****	—	—	changes in coastal ecosystems (y, n)	—

terrestrial ecosystems	changes in hydrology affect soil moisture content and evaporation rates (y, y)	land conversion owing to shifts in agricultural production (some y, n)	loss of saltmarsh and mangroves to sea-level rise (y, y)	∗∗∗∗∗	—	loss of keystone species (some y, n)	spread in mosquito-borne disease may encourage use of DDT (n, n)
oceans	—		—	declines in migratory freshwater fish (y, n)	∗∗∗∗∗	changes in marine productivity	
biodiversity	declines in species (some y, some y); construction of dams disrupts freshwater ecosystems	agricultural intensification reducing biodiversity (n, n)	loss of coastal wetlands (y, n)	changes in net primary production affect competition (e.g. savannah/scrub, lianas/trees) (some y, some y)	loss of calcifying species, potential disruption of marine ecosystem, in particular (n, n)	∗∗∗∗∗	declines owing to DDT use (n, n)
human health	water stress (y, y); construction of dams can lead to outbreaks of disease such as malaria and schistosomiasis (n, n)	malnutrition (y, y)	saltwater intrusion threatening water supplies; potential for disease post-coastal flooding (n, n)	loss of ecosystem services, e.g. C sinks, water purification, coastal protection; soil erosion, nature deficit syndrome (some y, n)	loss of fish stocks, loss of livelihoods of persons dependent on coral reef fish (y, y)	loss of medicinal plants (n, n); spread of infectious disease (y, y)	∗∗∗∗∗
settlements and infrastructure	subsidence (n, n); construction of dams can lead to inundation of settlements (n, n)	—	damage owing to storm surges (y, y)	—	—	—	—

Table 3. Some projected quantitative estimates of climate change impacts at 4°C about preindustrial levels under the A1B scenario in the 2080s taken from this volume and elsewhere.

impact sector	projections at 4°C above preindustrial	projections at 2°C above preindustrial	sources
hydrology	15% world population exposed to water stress; 840 million people experience increase in water stress globally; increase from present-day 1%, to future 30%, of global land area experiencing drought at any one time	410 million people experience increase in water stress globally; water stress reduced compared with 4°C in most river basins; in a small number where this is not so, benefits offset by changes in seasonality	[27,46,92]
agriculture and food	50% of land on which crops currently grown becomes unsuitable for cultivation; 15% of the globe's dry land currently suitable for cultivation becomes unsuitable; 20% of globe's colder lands become suitable for cultivation; limited adaptation options in sub-Saharan Africa; threats to food security	32% of land on which crops currently grown becomes unsuitable for cultivation; carefully planned adaptation could maintain food security in sub-Saharan Africa	[27,47]
coasts	sea-level rise of 0.5–2.0 m if occurs in 2100 (range includes accelerated ice melt); for median sea-level rise of approximately 0.47 m in 2100, i.e. excluding accelerated ice melt (www.avoid.uk.net), more than 30-fold increase in population experiencing coastal flooding	low risk of accelerated ice melt; for median sea-level rise of approximately 0.35 m in 2100, i.e. excluding accelerated ice melt (www.avoid.uk.net); about a 15-fold increase in population experiencing coastal flooding	[25,27,87, 90]
ecosystems	functional extinction of coral reef ecosystems (converted to algal mats); risks of extinction to approximately 40% species studied globally, including losses of iconic species and associated ecotourism; disruption to functioning of major global ecosystems, Arctic and salvanization of Amazon rainforest; conversion of terrestrial carbon sink to a source exacerbating climate change; large increase in boreal and Mediterranean fire frequency; 50% of protected areas cannot fulfil objective; major widespread loss of ecosystem services worldwide	all coral reefs bleached; risks of extinction to approximately 20% of species studied; some increases in fire frequency; damage to Arctic ecosystem functioning; ecosystem services reduced in some areas; Amazon forest largely intact	[32,43,46, 80,93]

oceans	further mean acidification by 0.26 pH units (in addition to the present-day change of 0.1 units); risk of disruption to marine ecosystems; risk of localized ocean anoxia	further acidification by up to 0.07 pH units; some damage to marine ecosystems	[89,94,95]
extreme weather	50% flood-prone people exposed to increased hazard; flood-affected population rises to 544 million annually (as defined by those experiencing a present-day 1 in 100 year flood)	25% flood-prone people exposed to increased hazard; flood-affected population rises to 211 million annually	[27,96]
human health	health hazards increasingly difficult to control	hazards reduced	[51]
impacts of feedback processes in the Earth system	loss of terrestrial carbon sink and hence large-scale loss of forests via dessication and fire (potentially including up to 50% Amazon (excluding deforestation) and uncertain fraction of boreal forest)	much reduced risk of loss of terrestrial carbon sink; Amazon likely to remain largely intact	[32,52,77,89, 93,98,99]

just beginning. Hence, climate change impacts on ecosystems may threaten our future ability to protect human health, especially as pathogens evolve resistance to current treatments.

Disturbance to forests in proximity to human habitation can lead to increased prevalence of disease. For example, Olson *et al.* [35] identified a 48 per cent increase in malaria incidence associated with a loss of 4.3 per cent of forest cover in a 3 year period. This can be via a reduction in populations of the disease vector's predators, or because of changing environmental conditions allowing them to outcompete benign related species [36]. Modelling these interactions into the future needs to be a priority for future research.

A significant proportion of the world's population is entirely dependent on fish. Cheung *et al.* [37] report on dramatic turnovers in fish assemblages for climate changes well below 4°C, particularly in the Arctic and Antarctic, potentially disrupting ecosystem functioning and numerous local extinctions in the subpolar regions, the tropics and semi-enclosed seas. Communities particularly at risk from changing fisheries resources are on small reef islands on the rim of atolls such as the Maldives [25].

Important linkages between climate change impacts on ecosystems and those upon agricultural and other systems are generally omitted from impacts assessments. For example, as bioclimatic envelopes of pest and disease vectors change, new pests and diseases may invade systems, requiring new disease-resistant crop varieties to maintain agricultural productivity [38]. Wild crop genotypes are an important resource yet climate change impacts upon these have only recently been considered [31]. However, quantifying potential risks to food production owing to loss of wild crop genotypes is not currently feasible. Several recent studies consider crop damage owing to pests in future decades [21] and highlight the importance of interactions between CO_2 concentrations and temperature, and precipitation in determining the size of these effects. It would be useful and feasible to explore ways to combine such projections with global agricultural models of climate change impacts on crops, which typically omit impacts of pests.

While many of the world's staple crops reproduce vegetatively, or via wind pollination, many others rely on pollinators. Over 80 per cent of the 264 crops grown in the EU depend on insect pollination [38]. However, few pollinator distributions have been modelled in relation to climate change. Quantifying potential risks is difficult because limited information exists on the relationship between crops, their pollinators and climate change. It is recommended to collect such information and carry out bioclimatic or ecophysiological modelling of species, or species groups, identified as the key pollinators in relation to their crops. Much more severe and more difficult to model are the potential interactions between wild species and pollinators.

(*b*) *Interactions mediated by human adaptation to climate change*

A key interaction omitted from modelling approaches is that between impacts in one sector and adaptation by humans to impacts in another sector. For example, there are potential consequences to health and ecosystem sectors resulting from human adaptation in agricultural, hydrological and coastal sectors.

Human adaptation to climate change-induced water stress can include anything from local collection of rainwater on buildings through the building of dams to unsustainable increases in groundwater abstraction. Dam construction can damage wetlands, inundate forests and may encourage reproduction of disease agents by concentrating them in lakes close to human habitation, as has occurred in Burkina Faso, Sudan and Egypt for schistosomiasis and malaria [36].

Even for small amounts of climate change it will become infeasible to continue to grow presently used crop varieties in tropical or desert areas where crops are already grown close to their thermal limits. By 4°C, crops in many regions are projected to be affected and adaptation over potentially large parts of the globe may be needed (table 3). This could include switching to new crop types, installing irrigation systems, agricultural intensification, shifting agricultural lands to new areas and/or the use of genetically modified crops resistant to future climates [1,4,17,20]. Changes to irrigation practices may exacerbate water stress and may reduce water supplies to wetlands, which themselves provide key ecosystem services. Agricultural intensification can have negative impacts, including increases in nutrient run-off into rivers and estuaries, where it may cause local anoxia and contribute to greenhouse gas emissions of N_2O [12]. The wholesale shifting of agricultural lands has profound implications, as discussed below.

Human adaptation responses to sea-level rise range from managed retreat, building of dykes and construction of flood barriers [26]. It is widely reported to be cost-effective to protect major cities against a sea-level rise of up to 2 m, but this, as the authors acknowledge, is only a partial analysis. The coastal protection considered only safeguards cities and does not protect coastal infrastructure away from cities, which may be extensive, nor does it avoid large-scale loss of coastal wetlands, mangroves and saltmarshes. Building of dykes to protect towns may be to the detriment of associated natural ecosystems [39], such as mangroves and saltmarshes where many marine fish species spawn. Such ecosystems also protect coastlines against storm surge and tsunamis [40]. Hence, cost-effectiveness analyses for coastal protection need to include losses of these ecosystems and the consequences for fisheries and coastal infrastructure.

This volume contains some of the few studies of climate change impacts considering climate change as great as 4°C. Table 3 collates some of the estimates appearing in this volume and elsewhere and compares them with estimates of impacts at 2°C. Several of these estimates are taken from the AVOID project [27]. Considering the large impacts in the agricultural, hydrological and ecosystem sectors expected in a 4°C world, future use of land and water would need to be carefully planned, taking into account the needs of humans, agriculture and ecosystems and their services.

In this context, limits (physical or financial) to simultaneous adaptation in multiple sectors need to be considered. The global cost of adapting to climate change from 2010 to 2050 (2°C) has been estimated to be $75–100 billion *each year* [41]. In the agricultural sector, Easterling *et al.* [21] estimated that climate change damages to wheat, rice and maize could be avoided by adaptation up to a limit of a temperature increase of 1.5–3°C in tropical regions and 4.5–5°C in temperate regions. Temperature changes of between 4 and 8°C are projected in the summer across various temperate and tropical regions for a global 4°C temperature rise [42]. This suggests that these adaptive capacities might be exceeded, especially in the areas with the larger temperate rises such as the USA, the Mediterranean and many parts of Africa [42]. Many of these studies do not include damage caused by concomitant increases in tropospheric ozone and extreme weather events, and so the estimated adaptive capacities might be over-optimistic. For ecosystems, while adaptation to a 2°C world is considered feasible, the options for adapting, either naturally or with human assistance, to a 4°C world are extremely limited, since at these temperatures few ecosystems would be expected to be able to maintain their current functioning [43].

(*c*) *Cross-regional interactions*

The mechanism by which climate change impacts in one region affect another can be direct, in which losses of human or natural capital in one region affect human or natural capital in another region, or indirect, in which the mechanism is via mitigation or adaptation practices taking place in one region having consequences for another. Declining agricultural yields in a given region can result in increased demand to import food from other areas. Such changes in supply and demand affect food prices globally [1,4,20].

Migration is already occurring away from some areas in response to desertification (Egypt) and flooding (Mozambique and Vietnam; [44]). Two billion people live in arid, semi-arid and sub-humid regions that are extremely vulnerable to water supply loss [45]. One-third of the world's population live in areas already under water stress, with the area of the planet subject to drought at any one time projected to dramatically increase ([46]; table 3). Some of these water-stressed areas are expected to become agriculturally or agro-economically non-viable. Table 3 shows the large numbers of people (some 800 million) exposed to increasing water stress, and 50 per cent of global cropland projected to become less suitable or unsuitable for cultivation in a 4°C world. In sub-Saharan Africa migration to highlands is a likely consequence [47]. Migration may be inevitable in areas where climate change will have a detrimental effect on already water-stressed agricultural areas such as northeastern Brazil [48]. Coastal systems currently hold some 40 per cent of the global population, and there is increasing immigration into these areas [25]. However, sea-level rises of 0.5–2.0 m are expected in a 4°C world (table 3). One estimate of climate change-induced migration suggests that 1.4–6.7 million Mexicans could migrate to the USA as a direct result of climate change-induced crop failure by the 2080s [49]. Estimates from empirical data about past climate variability and migration rates showed that a 10 per cent reduction in Mexican crop yields would lead to 2 per cent of the Mexican population emigrating. With larger reductions in crop yields projected for many parts of the world, notwithstanding the unique cross-border circumstances, this raises the potential for substantial human migrations, raising concerns about international stability [50]. Large-scale migration will also have impacts such as demand for land and water in the regions into which they move, not included in current assessments of impacts. This will be particularly important in a 4°C world. The synergy of these impacts shown in table 3 could induce dramatic changes in where people live and practise agriculture. Hunger, starvation, conflict and population movement may be widespread [51].

There has been little study of the potential mechanisms for cross-regional interaction in modelling exercises and a process-based simulation of migration is almost certainly infeasible owing to the complex nature of personal migration-related decision-making [52]. Rather, a scenario-based approach to possible future migration patterns is recommended, so that climate impact projections, already dependent on future downscaled population projections (e.g. [1]), can be made consistent with scenarios for population movement.

An estimated 50 per cent of the impacts on water stress and crop suitability could be avoided by constraining climate change to 2°C (table 3; [27]). In this situation, the potential for large-scale migration and displacement agriculture will therefore be less and potentially more likely to remain within the adaptive capacity of the human and natural systems concerned.

(*d*) *Climate change mitigation and land-use change*

Changes in land use can have large impacts on the global and local climate. For example, deforestation releases carbon from removed vegetation and soils, and the surface albedo changes significantly. Forests such as the Amazon 'recycle' their water and hence forest loss can contribute to drying [53]. Climate change mitigation could involve significant reductions in deforestation as this is regarded as one of the most cost-effective methods of reducing emissions, and there is widespread consideration of the introduction of a political mechanism for so-doing (Reducing Emissions from Deforestation and Degradation; REDD).

However, human adaptation to climate change impacts might induce shifts of agriculture away from drying areas and into areas currently covered by forests. Hence, projections of impacts on ecosystems might be exacerbated by further conversion of natural ecosystems to agricultural systems (table 2). This can have additional implications for human health, by creating conditions under which disease vectors thrive close to human habitation [36].

Afforestation can also contribute to climate change mitigation through carbon sequestration, with positive or negative implications for biodiversity and ecosystem services. Attempts to create forests in areas currently supporting high non-forest biodiversity, or by using non-native tree species, can have a negative impact on native biodiversity, and may not succeed since soils may not be suitable. Planting of native trees in previously degraded or deforested areas is beneficial to biodiversity and ecosystem services, and can enhance connectivity in forest ecosystems, aiding in adaptation [43]. Benefits of afforestation accrue slowly over the long time scales required to recapture the carbon lost from an area that has originally been deforested [54]. For this reason, 1 ha of afforestation does not effectively compensate for 1 ha of deforestation and this is an important factor in the interaction of climate change mitigation and land-use planning.

A 4°C world would induce changes in the distribution of the human population, its diet, its agricultural systems and its ecosystems, concentrating all three in areas remaining sufficiently wet. The study of these interactions is still in its infancy. IMAGE has been used to explore agricultural trade liberalization in the context of climate change, showing how it would encourage expansion of agricultural land in Latin America and southern Africa, increasing pressure on ecosystems [4]. The cost of reaching 2050 emissions reduction goals (80% lower than 2000 levels) could be cut by 50 per cent if agricultural production transitioned from meat-based to plant-based diets, based on the abandonment of 2700 Mha of pastureland and also from reductions in greenhouse gas emissions from agriculture [55]. Efforts to assist natural ecosystems to adapt to climate change include enhancing connectivity between areas. Spatial planning issues connected with planned adaptation in agricultural and human systems will need to be integrated with adaptation of ecosystems and ecosystem services.

Stringent mitigation of greenhouse gas emissions will require large-scale deployment of renewable energy generation and/or biomass cropping. Both of these have significant interactions with land use. For biofuel or biomass cropping, the land required for this must displace either agricultural land, marginal land or natural ecosystems [56]. This displacement of agricultural land may be increased by the negative climate change impacts on sugarcane yields [57]. Displacement of agricultural land will influence world food supply and prices, as has already occurred during the food price crisis of 2007/2008 [58], and will have impacts for risks of malnutrition. Holistic management of both fossil fuel emissions and the terrestrial biosphere through expansion of forests and unmanaged ecosystems would lower mitigation costs [59], but food prices could rise owing to the pressure on agricultural land. If, instead, shifting (adapting) agricultural systems causes deforestation or unmanaged ecosystem loss, this will reduce the resilience of ecosystems to climate change. Similarly, biofuel cropping, nuclear power plants and carbon capture and storage plants all require large amounts of water. Thus, mitigation efforts have potential complex interactions with climate change impacts on agriculture and ecosystems.

Key interactions also occur between climate change and the operation of renewable energy in the future, and between land-use planning and the siting of renewable energy plants. A major benefit of mitigation is the protection of vulnerable people and ecosystems from climate change, and unintentional negative impacts of renewable energy schemes can be prevented by careful siting of plant. Deployment of renewable energy, nuclear power, and carbon capture and storage schemes needs to be planned around future climates, rather than making an assumption that current wind, water or solar resources will be available for some decades in the same location in the future. Careful assessment can avoid potential ‘mal-mitigation’ where mitigation efforts could either fail entirely or produce largely avoidable local negative side effects.

(*e*) *Regionally coincident impacts*

Spatially coincident impacts in different sectors could have a disproportionate effect on the human population and ecosystems of a given region. Many climate change projections refer to large regions, while on the ground a diverse pattern of gains and losses may exist within an overall picture of regional loss. However, impacts that occur in the same region, even if not precisely spatially coincident, may have a disproportionate effect on a region’s economy owing to multiple stresses placed upon the system. The IPCC [46] reports on coincident hunger, sea-level rise and water resource scarcity impacts in Asia; and coincident water stress and malnutrition in Africa. Since most of the literature assessed by the IPCC [46] refers to global temperature rises of less than 4°C, such coincident impacts would be expected to be much more widespread and severe in a 4°C world.

(*f*) *Extreme weather events*

In the coming decades, one of the most serious impacts of climate change is projected to be the consequences of the projected increases in extreme weather events. For example, climate change-induced changes in precipitation patterns and changes in climate variability would increase the area of the globe experiencing drought at any one time from today's 1 per cent to a future 30 per cent by the end of the twenty-first century [46]. An increasing number of studies now project global trends in how extremes will change in the future using GCM and/or regional climate model (RCM) output (e.g. [60,61]). However, uncertainties in these projections are large, particularly for precipitation, with some changes of opposite sign. Some studies have focused on the regional uncertainties of projecting extremes, in particular for projection of increased European drought (e.g. [62,63] and references therein). Limited work exists for other continents.

Few studies examine the potential consequences of these increases in extreme weather upon individual sectors and/or regions, but these could be significant. Only a few days of high temperatures near flowering in wheat, groundnut and soybean can drastically reduce yield [64], while maize losses could potentially double owing to floods in the USA [65]; and the AVOID study [27] estimated that, in a 4°C world, 50 per cent of fluvial flood-prone people would be exposed to increased flood risk compared with approximately 25 per cent in a 2°C world.

Biophysical IAMs and other regionally and sectorally specific climate change impact models can simulate changes in the frequency and the intensity of extreme weather events if:

— the impact model is formulated to take account of, for example, the effect of continuous periods of dry days or dry months (for long-term drought), or the number of days over which temperatures exceed a particular threshold (for heatwaves), or daily time series of rainfall (for heavy precipitation events). Many process-based physical impact models require climate inputs in the form of a daily time series. Simple IAMs are not capable of representing such processes in detail, although PAGE attempts to provide a scenario that accounts for increases in extremes. Cumulative distribution functions might be constructed from statistical relationships between extremes and predictor variables used in these simple IAMs [3], enabling them to better represent the impacts of extremes.

— the climate change projections provided to the model are at the appropriate temporal resolution (monthly for droughts, and daily for most other extreme weather events), and include projected increases in extremes. Considering probability distributions (pdf) of climatic parameters, extreme events may increase for: a shift in the mean climate; a shift in the variance; or an increase in its skewness. For example, monthly future climates can be produced by pattern-scaling GCM outputs as in SCENGEN [66], after which a weather generator derives a daily time series. In these studies, changes in the frequency of extreme weather events can only occur as a result of changes in mean climate and as a result of changes in variability or skewness. However, the approach can capture long-term droughts since the monthly changes in precipitation derived from the GCM patterns are incorporated in the analyses [63]. New approaches in ClimGEN and/or the further development of weather generators may allow representation of changes in variability and/or skewness in biophysical IAMs [3,66,67].

(*g*) *Interactions within sectors generally not combined within analyses*

Dynamic global vegetation models (DGVMs) and bioclimate envelope models are commonly used to project climate change impacts on ecosystems. DGVMs consider the cycling of biomass, carbon, nutrients and water between ecosystems and the atmosphere, using detailed land-surface schemes that capture interactions in detail [68]. However, they model ecosystems as plant functional types and do not consider responses of individual species. In contrast, bioclimatic models use empirical statistical correlations between meteorological variables and species presence [69,70] to derive predictors for species distributions. Such predictors appear to work well at large scales—with precipitation and temperature variables being tied to direct and indirect processes.

However, DGVMs treat ecosystems simply as a functional type, so that impacts on biodiversity are not adequately assessed, while the bioclimatic envelope approach is generally applied to one species at a time and interactions between species are not considered. A few studies examine the combined effects of climate change on plants and their pollinators [71] or on predators and their prey, or on how the spread of disease might induce extinction of some species (e.g. [72]). Attempts by one species to survive a changed climate by moving to higher latitudes and altitudes might result in that species becoming invasive in the new environment it has colonized. However, for the majority of species, the effects of climate change on such interactions have not been considered, and this is potentially significant in terms of unforeseen disruption to ecosystem functioning [73].

Climate change impacts to forest trees have been estimated by both DGVMs and bioclimatic models (e.g. [67,74,75]), while at the same time other models are used to project future incidence of forest fire (e.g. [76–78]), while still others simulate outbreaks of pests [79]. In a 4°C world, soil carbon cycle feedback processes are projected to lead to widespread forest loss, especially in the Amazon (e.g. [78,79]). These simultaneous effects have not yet been combined in any quantitative analysis, but overall must lead to a more pessimistic view.

Climate change impacts on species have been widely calculated (Warren *et al.* [80] present a meta-analysis), but there are only limited studies on keystone species that affect overall ecosystem functioning. For example, potential declines in krill, a keystone species in the Southern Ocean, have been identified [81] and this will have impacts on many other species. Ocean acidification threatens the potential for coral reefs, coccolithiphores, molluscs and other shell-forming ocean inhabitants to survive [82,83]. Only for coral reefs has this research been combined with impacts of increases in sea surface temperature in projecting thresholds for survival [84]. Changes in marine productivity might well be expected as the ocean acidifies, and the consequences of this are unknown [46]. Similarly, projected climate change impacts on fish [37] include climate change impacts on larval dispersal but omit loss of nursery habitat.

In agricultural systems, the wide range of studies reviewed by the IPCC [46] variously include CO_2 fertilization effects (in some cases with appropriate treatment of uncertainty therein), methods of adaptation, the potential for agriculture to move to new areas and global trade in crops. However, no single approach incorporates all of these features. As mentioned earlier, it would be useful to explore how climate change-induced projected increases in outbreaks of agricultural pests and diseases could be incorporated in agricultural models. Increases in fossil fuel burning also lead to increases in tropospheric ozone levels that damage crops and trees—also not generally included in models assessing climate change impacts on agriculture or ecosystems [1,20,85]. However, increases in tropospheric ozone and their impacts on crops and trees have been projected independently (Felzer *et al.* [86] review recent studies) and it would not be difficult to combine such models. Tropospheric ozone also damages human health, highlighting the need to combine assessments of climate change damage with those of the air pollution resulting from the emission of the same pollutants.

(*h*) *Feedback processes in the Earth system*

While many feedback processes are represented in global climate change models and thus indirectly in the simple models emulating them, recent observations are showing that some processes, in particular the melting of Greenland and West Antarctic Ice Sheets and the Arctic sea ice, are proceeding more rapidly than in models [87,88]. This indicates that the Earth may be more sensitive to the current levels of warming than GCMs are projecting. A more significant potential feedback is the release of marine methane hydrates. This could result in a progressive release, over a 1000–100 000 year time scale, of about twice the amount of fossil fuel carbon emitted [89]. The potential release rate on shorter time scales has not been estimated but could exacerbate warming, as could the currently increasing release of methane from permafrost [90]. Other feedback processes such as changes in albedo as a result of climate change-induced forest dieback, or increased desertification, are included in some GCMs [53]. However, some climate change impacts such as losses of forest owing to pine-bark or spruce-budworm attack, in combination with increased incidence of fire, might alter albedo in some areas. Such an interaction could usefully be modelled. As knowledge about the processes underlying feedbacks in the Earth system improves, they can be included in GCMs and thus be reflected also in projections of climate change impacts. Finally, climate change impacts are projected to cause reductions in economic growth, with estimated losses depending on the assumed discount rate, and rising as high as 5–20% of GDP [91]. Such losses might reduce anthropogenic greenhouse gas emissions: an effect potentially much larger than any increase in emissions caused by additional demand for air conditioning. However, models that provide integrated assessment of climate change impacts and the economy [1] generally represent climate change impacts poorly and usually omit Earth system feedback effects entirely [6].

3. Discussion

Table 3 shows that a 4°C world would be facing enormous adaptation challenges in the agricultural sector, with large areas of cropland becoming unsuitable for cultivation, and declining agricultural yields. This world would also rapidly be losing its ecosystem services, owing to large losses in biodiversity, forests, coastal wetlands, mangroves and saltmarshes, and terrestrial carbon stores, supported by an acidified and potentially dysfunctional marine ecosystem. Drought and desertification would be widespread, with large numbers of people experiencing increased water stress, and others experiencing changes in seasonality of water supply. There would be a need to shift agricultural cropping to new areas, impinging on unmanaged ecosystems and decreasing their resilience; and large-scale adaptation to sea-level rise would be necessary. Human and natural systems would be subject to increasing levels of agricultural pests and diseases, and increases in the frequency and intensity of extreme weather events.

In such a 4°C world, the limits for human adaptation are likely to be exceeded in many parts of the world, while the limits for adaptation for natural systems would largely be exceeded throughout the world. Hence, the ecosystem services upon which human livelihoods depend would not be preserved. Even though some studies have suggested that adaptation in some areas might still be feasible for human systems, such assessments have generally not taken into account lost ecosystem services. Climate change impacts, especially drought and sea-level rise, are likely to lead to human migration as people attempt to seek livelihoods elsewhere.

This paper has highlighted the further challenges presented by the interactions between climate change impacts, in which coincident or interacting impacts within and between sectors and regions may present a greater challenge than the sum of the challenge of adapting to each impact in each region if these were independent. It has drawn attention to the interaction between human adaptation processes and impacts in various sectors. Importantly, it has also highlighted the interaction between climate change impacts upon terrestrial and coastal ecosystems and human sectors such as agriculture and human health. These interaction processes will increase as their drivers increase, and will be much more significant in a 4°C world than in a 2°C world.

Were global average temperatures to rise by 2°C and not increase further, some 50 per cent of the impacts to human systems could potentially be prevented (table 3 and [27]), and ecosystem services would, in large part, be expected to be generally preserved (table 3). While some areas would experience drying, as table 3 shows the impacts on agriculture and hydrology, and sea-level rise, would be expected to be much lower than in the 4°C case, and similarly the challenge to adaptation to these effects and their interactions would also be much lower. Local-scale damage to some ecosystems, including extinctions, and disruption to coral reef and ice-based ecosystems would still be expected, but the worst losses might be prevented. Conservation planning might be able to assist with the adaptation of natural ecosystems to this level of temperature rise.

The role of land-use change at the nexus between climate change mitigation and adaptation and agricultural and natural ecosystems has been highlighted, with particular reference to biofuel cropping, agricultural intensification and diet. The spatial planning of land use when attempting to simultaneously adapt agricultural, human, coastal and natural ecosystems to a changing climate, with or without significant mitigation, has been highlighted as very important. This will be particularly important for mitigation planning when aiming for a 2°C world. Such an approach might be termed 'ecosystem-based mitigation'.

Only a limited proportion of these interactions is currently captured by modelling processes, in particular the simple IAMs commonly used for cost–benefit analysis. While some interactions appear too uncertain to capture within models (e.g. with human migration), there is a need to represent others, especially the possible consequences of large-scale adaptation. Process-based IAMs such as

IMAGE, CIAS and GCAM are best prepared to assess these interactions and IMAGE and GCAM have already been applied to examine some of the links between land-use change, climate change and agricultural systems.

As climate changes, the drier regions of the planet are projected to become less and less habitable owing to increases in drought and desertification. Many humans and ecosystems would be expected to be forced to adapt by attempting to move into areas remaining sufficiently wet and not inundated by sea-level rise. This would result in a concentration of the human population, agriculture and remaining biodiversity in a contracting land area, leading to increasing competition for land and water. Integrated models could usefully be applied to determine when land and water supplies may become insufficient to satisfy the needs of human systems and the ecosystem services (such as wetlands, forests and biodiversity in general) supporting livelihoods.

4. Conclusion

This paper has highlighted the complexity of a 4°C world and the wide-ranging consequences of direct and indirect human and natural impacts and adaptation to climate change. Only a limited number of these interactions has so far been captured by models.

Any attempt to debate an acceptable level of mitigation for global greenhouse gas emissions needs to take into account not only the projected climate change impacts but also the considered limits to adaptation in each sector and region; the potential for interactions between the impacts; the potential consequences of adaptation in one sector on other sectors and regions; whether there is sufficient land and water to deliver the required combination of adaptation and mitigation; and how land use, agricultural and climate policies are inextricably linked. This highlights the need for ecosystem-based mitigation as well as ecosystem-based adaptation. Lack of consideration of such key linkages risks a significant underestimation of the challenge that simultaneous adaptation in multiple sectors and regions at multiple scales, while subject to ever-increasing extreme weather, presents. Consideration of such linkages thus adds significantly to the incentive to avoid a 4°C world.

While the impacts of climate change are projected to be smaller and less widespread for global mean temperature rises of 2°C as opposed to 4°C, interactions between mitigation processes and adaptation and climate change impacts, and the resultant demands for land and water, will be of great importance.

Issues of land-use change and human migration are currently inadequately addressed in most studies, and there is a fundamental lack of incorporation of the role of ecosystem services. This review has suggested how modelling approaches might be improved to cover interactions more fully, while recommending that processes such as migration need to be handled using a scenario approach. Other omitted interactions are too difficult to quantify or to combine with mainstream sectoral studies and need to be combined qualitatively with modelling approaches.

The context of the potential for large-scale feedbacks in the Earth system to exacerbate climate change and consequent impacts and interactions for any given future emission scenario beyond levels currently estimated by state-of-the-art modelling approaches needs to be taken into account. Such feedbacks are much more likely to operate in a 4°C world, potentially increasing global mean temperature rise still further. These risks would be much reduced in a 2°C world.

Table 3's synthesis of impacts in a 2°C and 4°C world includes results produced by the AVOID project (www.avoid.uk.net), which is funded by the UK Department of the Environment, Food and Rural Affairs.

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