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Estimating global impacts from climate change

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Abstract

We surveyed the literature to assess the state of knowledge with regard to the (presumed) benefits or avoided damages of reducing atmospheric concentrations of greenhouse gases to progressively lower levels. The survey included only published studies addressing global impacts of climate change; studies that only addressed regional impacts were not included. The metric we used for change in climate is increase in global mean temperature (GMT). The focus of the analysis centred on determining the general shape of the damage curve, expressed as a function of GMT. Studies in sea level rise, agriculture, water resources, human health, energy, terrestrial ecosystems productivity, forestry, biodiversity, and marine ecosystems productivity were examined. In addition, we analysed several studies that aggregate results across sectors. Results are presented using metrics as reported in the surveyed studies and thus are not aggregated.

We found that the relationships between GMT and impacts are not consistent across sectors. Some of the sectors exhibit increasing adverse impacts with increasing GMT, in particular coastal resources, biodiversity, and possibly marine ecosystem productivity. Some sectors are characterised by a parabolic relationship between temperature and impacts (benefits at lower GMT increases, damages at higher GMT increases), in particular, agriculture, terrestrial ecosystem productivity, and possibly forestry. The relationship between global impacts and increase in GMT for water, health, energy, and aggregate impacts appears to be uncertain. One consistent pattern is that beyond an approximate 3–4°C increase in GMT, all of the studies we examined, with the possible exception of forestry, show increasing adverse impacts. Thus, in total, it appears likely that there are increasing adverse impacts at higher increases in GMT. We were unable to determine the relationship between total impacts and climate change up to a 3–4°C increase in GMT. There are important uncertainties in the studies we surveyed that prevent us from a precise identification of 3–4°C as the critical temperature transition range, beyond which damages are adverse and increasing. We are confident in general however, that beyond several degrees of GMT, damages tend to be adverse and increasing. We conclude by suggesting some priorities for future research that, if undertaken, would further our understanding of how impacts are apt to vary with increases in GMT.

Keywords: Global impacts of climate change; Agriculture; Forestry; Water; Ecosystems; Biodiversity; Human health impacts of climate change

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has concluded that the costs of reducing emissions to stabilise atmospheric greenhouse concentrations rise with successively lower levels of stabilisation. Costs rise as concentrations are decreased from 650 to 550 ppm CO_2 and then rise more sharply as concentrations are decreased from 550 to 450 ppm (Metz et al., 2001). An important question is how the *marginal* benefits, or avoided damages, associated with controlling climate vary with particular levels of mitigation. In other words, what are the (presumed) benefits or avoided damages of reducing atmospheric concentrations of greenhouse gases to progressively lower levels?[1] Do the marginal benefits increase or decrease at successively lower levels of greenhouse gas concentrations? A number of previous studies have attempted to address these questions. Some have focused on quantifying the benefits of stabilising climate at particular levels, typically expressing those benefits in terms of a single metric, most often dollars, which allows for a direct comparison of the benefits of controlling climate change to the greenhouse gas emission control

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[1] See Questions 3 and 6 in the IPCC Synthesis Report (Watson and The Core Writing Team, 2001).

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costs necessary for doing so (e.g., Fankhauser, 1995; Nordhaus and Boyer, 2000; Tol, 2002a). Some use non-monetary units (Alcamo et al., 1998). Others have sought to identify important climate thresholds (e.g., Smith et al., 2001). However, the approaches employed in these studies have some important limitations.

While studies that aggregate impacts from climate change in terms of a single metric provide useful insight about how marginal impacts change, especially at higher levels of climate change, there are a number of concerns with them. One is that the common metric, particularly if it is dollars, may be difficult to apply to sectors that involve services that are not traded in markets and can also undervalue impacts in developing countries. A second is that it may actually be more useful for policy purposes to express results sector by sector rather than as a single aggregate, to show how the response to climate change can vary across sectors.

In this study, we identified the global marginal benefits associated with different levels of climate change in a sector-by-sector fashion. We did so based on a survey of primarily sectoral studies that have attempted to quantify global impacts of climate change. Instead of converting impacts to a common metric such as dollars, we retained the different metrics reported by the authors. Our goal was not to develop a single estimate of global benefits across sectors, but to examine the relationships between climate change and impacts in particular sectors to discern any general patterns.

2. Method

We examined the following sectors:

- coastal resources
- agriculture
- water resources
- human health
- energy
- terrestrial ecosystems productivity
- forestry
- terrestrial biodiversity
- marine ecosystems productivity

To the extent of our knowledge, no published studies investigated global recreation, tourism, human amenity value, or migration; also, local and regional impacts in these sectors could be substantial (e.g., Lise and Tol, 2002). We also examined recent studies that estimated aggregate impacts (cross sectoral) on a global scale.

We present results using the metrics as they are reported in these studies, which is a broad range of units (e.g., change in GDP, number of people affected, agricultural production, and primary productivity). Each of these metrics has advantages and disadvantages, many of which are discussed in the studies. We note above some limitations associated with using a monetary metric, but also affirm that this sort of metric is appropriate to measure impacts on markets. Number of people at risk is similarly a sensible numeraire in sectors in which ultimately impacts on people are of greatest concern (agriculture, coastal resources, health), and it also has the advantage of allowing for cross-sectoral and regional comparisons to some extent. This metric counts all individuals the same and in some sense is more equitable than the monetary numeraire. But it does not measure intensity of impact (see Schneider et al., 2000 on multiple numeraires).

We used global mean temperature (GMT) as the index for measuring change in climate. For any concentration of greenhouse gases, there is a range of potential changes in climate (Houghton et al., 2001). Furthermore, for any change in GMT there is a range of concomitant changes in global precipitation and other meteorological variables. A wide range of potential regional patterns of climate change is also associated with a particular change in GMT. Variation in these regional patterns can have a profound effect on regional impacts and even net global impacts. Thus, one would expect an examination of the type we undertook to yield a wide range of potential impacts for any given GMT. We used GMT because it is the most feasible index of climate change, but note its limitations (see Smith et al., 2001). Regional impacts are discussed in only limited fashion to highlight the point that they often differ substantially from global impacts.

Our analysis focussed on determining the general shape of the damage curve, expressed as a function of GMT. We attempted to determine whether impacts appear with a small amount of warming and increase with higher levels of warming. If they did, we sought to determine if they would increase linearly or exponentially with increasing GMT, or whether they would stabilise at a particular level. We also looked for thresholds below which there are no impacts and cases where the relationship between impacts and climate change might be parabolic (e.g., net benefits and then damages). These questions are important because their answers determine whether there are benefits associated with lower GMT and whether those benefits remain constant, decrease, or increase as GMT rises.

Most of the studies we examined used output from general circulation models (GCMs) for simulating future climate (typically equilibrium model runs of doubled CO_2 in older studies and transient model runs in more recent studies). We took a cross-model approach, comparing impacts simulated by climate input from different GCMs. One difficulty with such an approach is that not only can factors such as precipitation be drastically different from model to model, but also regional patterns of temperature may differ (making it more challenging to compare regional impacts). A further limitation is that most studies use only a few GCMs, limiting the output we could analyse. Elucidating the relationship between impacts and GMT is not always straightforward given the few data points that most studies provide and we note this as a central limitation of our analysis. Where possible, we used literature on the underlying biophysical relationships with climate to bolster our conclusions regarding the shapes of damage curves.

We also examined the studies to determine how they differed from one another in several important elements. These differences point to some of the limitations of our approach of comparing results across studies. First, the scenarios of climate change that the various studies examined are often quite different. Houghton et al. (2001) concluded that GMT could increase by 1.4–5.8°C above 1990 levels by 2100. Few of the studies we examined encompass this full range. Furthermore, few studies also considered the impacts from changes in climate other than gradual increase average conditions, such as changes in extreme events or climate variance. Rate of climate change is also an important dynamic that has generally not been examined. Similarly, the time frames examined by most studies typically differ. As noted above, some studies examined results from different climate models in what is essentially a single point in time. Others examined time slices from a dynamic climate model run. Comparing the results from the two different approaches can be problematic, not least of so because of differences in socio-economic variables at different points in time. We also noted differences in the studies with respect to treatment of key factors such as adaptation, socio-economic baseline changes, sectoral interactions (water availability on agriculture for instance), and assumptions concerning biophysical processes such as carbon dioxide fertilization. Studies differ significantly in the role or influence that they posit these factors have, or the realism with which they are modelled. Finally, while we were interested primarily in global results, the spatial and distributional scales at which studies estimate impacts are often different.

3. Results

3.1. coastal resources

We examined two studies that investigated the effects of rising sea level: Fankhauser (1995) and Nicholls et al. (1999). A key difference in how adverse impacts from sea level rise were estimated in each of these studies has to do with what was assumed in terms of adaptation. With sea level rise, adaptation typically refers to the decision of whether or not to protect coastal development. Fankhauser assumed an economic paradigm of optimal protection, based on benefit-cost analysis, while Nicholls et al. used a more arbitrary approach based on observed practices. The Fankhauser study minimised the discounted sum of three streams of costs—protection costs, dryland loss, and wetland loss—for each region it considered. Central to this effort, Fankhauser estimated the optimal degree of coastal protection, where protection efforts would be undertaken if the benefits from avoided damage were estimated to exceed the incremental costs of additional action. Fankhauser presented the direct costs of sea level rise as a function of the assumed magnitude of that rise.

Nicholls et al. (1999) used a flood model algorithm similar to that employed by Hoozemans et al. (1993). This algorithm uses transient output from two GCMs along with results from an ice melt model to derive global sea level rise scenarios. Storm surge flood curves are then raised by relative sea level rise scenarios. Nicholls et al. estimated land areas threatened by different probability floods arising from several scenarios. These land areas were then converted to *people in the hazard zone* (the number of people living below the 1000-year storm surge elevation). Lastly, the standard of protection was used to calculate *average annual people flooded* (the average annual number of people who experience flooding by storm surge) and *people to respond* (the average annual number of people who experience flooding by storm surge more than once per year).

The results from both Fankhauser (Fig. 1, panel a) and Nicholls et al. (Fig. 1, panel b) suggest that adverse impacts increase linearly with sea level rise. As Fankhauser pointed out, one might expect protection costs to rise nonlinearly with sea level rise, because construction costs of sea walls increase with required height. This might well be the case, but costs of land and wetland loss dominate Fankhauser's bottom line. Ultimately, where wetland loss was the only damage associated with sea level rise, this might suggest a levelling off of adverse impacts, since there is a finite area of wetlands to be lost. Fankhauser's results are sensitive to choice of discount rate, and he assumed a discount rate of zero. Nicholls et al. projected that the number of additional people in the hazard zone also increases linearly as a function of sea level rise. The results displayed in panel b assume protection standards increase as incomes rise, though not in response to sea level rise. The second curve, which displays the results for people to respond as a function of sea level (those who are apt to migrate out of the coastal zone because of repeated flooding), exhibits a somewhat steeper increase after a 2°C increase in GMT (roughly 0.25 m sea level rise), which is assumed to occur by the 2050s. Nicholls et al. indicated that this is due mainly to the increased frequency of flooding within the existing

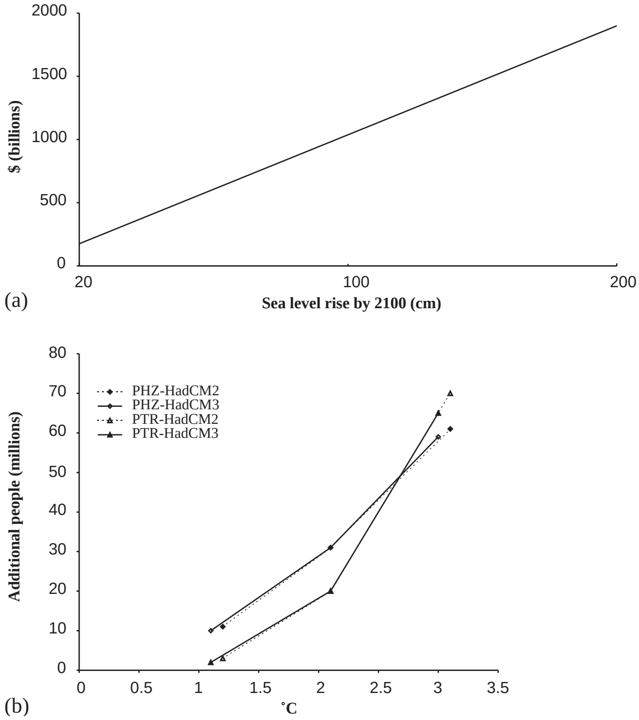

Fig. 1. Coastal resources: (a) costs of sea level rise in OECD countries. Data source: Fankhauser (1995). (b) Additional people in the hazard zone as well as people to respond as a function of temperature. Data source: Nicholls et al. (1999).

flood plain as sea level rises. The expansion of the size of the flood plain is a smaller effect.

In general, based on these results and the underlying relationship between sea level and impacts, we are highly confident that adverse impacts will increase with GMT increase and sea level rise. While it is impossible to determine whether the relationship between impacts and sea level is a straight line or exponential, the studies we examined are consistent with this more general conclusion; more land will be inundated as sea level rises, damages from higher storm surges will mount, and costs will increase as coastal defences are raised or lengthened to provide necessary additional protection. In addition, there will be other adverse impacts such as increased saltwater intrusion.

3.2. Agriculture

We examined four studies that investigated the possible effects of climate change on global agricultural production: Darwin et al. (1995), Rosenzweig et al. (1995), Parry et al. (1999), and Fischer et al. (2002). Rosenzweig et al. (1995), Parry et al. (1999), and Fischer et al. (2002) generated estimates of the number of people at risk of hunger (defined as those with an income insufficient to either produce or procure their food requirements). Darwin et al. (1995) and Fischer et al. (2002) also examined changes in the global production of agricultural commodities.

Rosenzweig et al. (1995) used a crop yield model linked to a world food trade model. The Parry et al. (1999) model system, like Rosenzweig et al., relied on two main steps, estimating potential changes in crop yields and estimating world food trade responses. Darwin et al. (1995) used a framework composed of a geographic information system (GIS) and a computable general equilibrium (CGE) economic model. The basic premise is that climate change would affect not only agriculture but also all manner of production possibilities associated with land and water resources throughout the world, including livestock, forestry, mining, and manufacturing, among others. The resultant shifts in regional production possibilities would alter patterns of world agricultural output and trade. Fischer et al. (2002) took a somewhat different approach, developing a global spatial data base of land resources and associated crop production potentials. Current land resources were characterised according to a number of potential constraints, including climate, soils, landform, and land cover. Potential output was determined for each land class for different varieties of crop. Future output was projected by matching the characteristics and extent of future agricultural land to this inventory. The economic implications of these changes in agro-ecology and the consequences for regional and global food systems were explored using a world food trade model, the Basic Linked System.

The results of the four studies paint a fairly consistent picture of how agriculture might be affected by changes in temperature. Rosenzweig et al. (1995) (Fig. 2, panel a) suggests a steeply increasing trend in adverse impacts, measured as a percentage change in the number of people at risk of hunger above about 4°C. In contrast, the results of the low temperature (GISS-A) scenario in the Rosenzweig et al. study suggest that benefits might actually exist at lower temperatures. This GISS-A scenario, unlike the other Rosenzweig et al. (1995) scenarios, does not incorporate farm level adaptation. Accordingly, benefits at low temperatures might be larger than the Rosenzweig et al. (1995) results indicate. It is also clear from the plot that at each level of temperature change, the more optimistic (level 2) scenario of adaptation reduces adverse impacts. While only one low temperature point indicates initial benefits, the results do seem to suggest a parabolic damage curve.

Parry et al.'s (1999) results, also shown in panel a, indicate adverse impacts at approximately 1°C, and the impacts increase sharply above approximately 2°C. HadCM2, with higher levels of CO_2, seems to lead to predictions of lower risk of hunger in the 2050s and 2080s relative to HadCM3. The fact that these curves become steeper over time may well result as much from a larger, more vulnerable exposed population in 2080 as from increases in temperature.

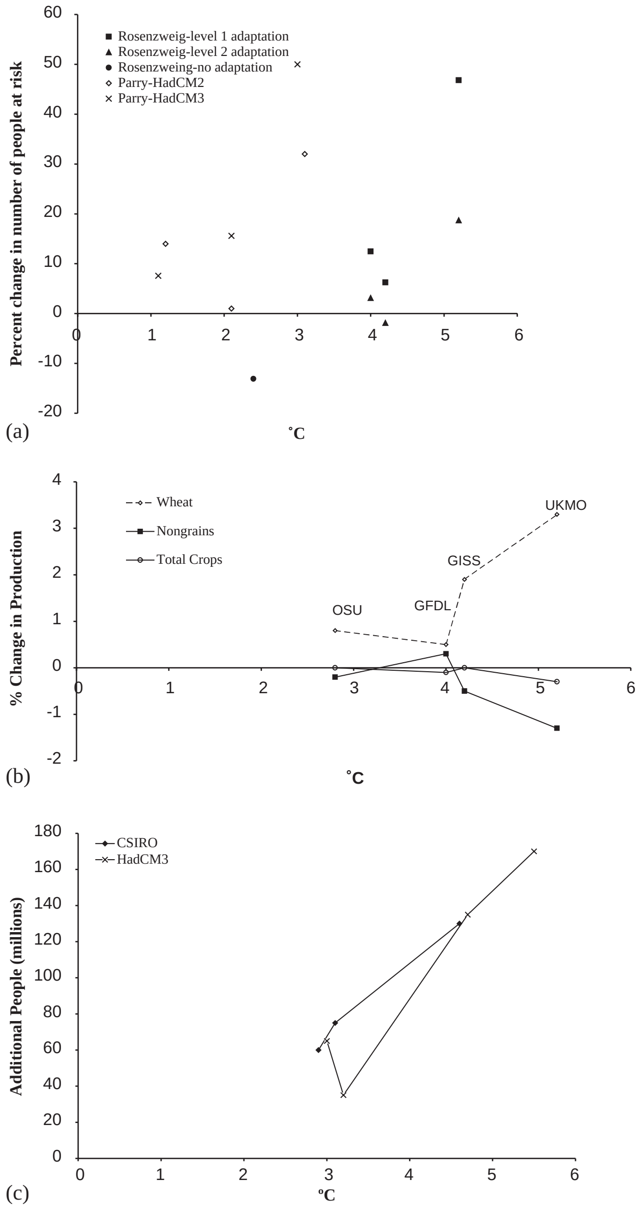

Fig. 2. Agriculture: (a) percent change in number of people at risk of hunger as a function of temperature. Panel a shows results derived from both Rosenzweig et al. (1995) and Parry et al. (1999). Impacts from Rosenzweig et al. represent cross GCM comparisons for an equilibrium doubling of CO_2 and are shown for three different levels of adaptation. Impacts from Parry et al. are taken from transient runs of the HadCM2 and HadCM3 GCMs and shown as averages for the decades of the 2020s, 2050s and 2080s. Data sources: Rosenzweig et al. (1995) and Parry et al. (1999). (b) Percent change in agricultural production as a function of temperature. Panel b plots results from Darwin et al. (1995) that show the change in production for various categories of crops. Data source: Darwin et al. (1995). (c) Increase in number of people at risk of hunger due to climate change in the 2080s. Data source: Fischer et al. (2002).

Darwin et al.'s (1995) results (Fig. 2, panel b) are more ambiguous, but do indicate a decrease in production in non-grain crops above 4°C. Production in total crops may also begin to decrease above this 4°C threshold. This reduction in total crops is offset by a sharp increase in the production of wheat above 4°C, driven by increases in wheat production in Canada and the United States. Nevertheless, the overall effect is pronounced. The basic trend, with the specific exception of wheat production, remains the same: increasing adverse impacts and increasingly steep impact curves.[2]

Fischer et al. (2002) did not present results as a function of global mean temperature. However, by examining temporal results across various scenarios and knowing how temperature changes for the various GCMs and forcing scenarios, we were able to deduce such results. Fig. 2, panel c shows the increase in the number of people at risk of hunger as a function of global mean temperature. Results are shown for two GCMs. It should be noted that because presenting results in this fashion relies on looking across scenarios, neither CO_2 nor precipitation is constant. This may help to explain the downturn in number of people at risk in the HadCM3 results. In general, however, both models show that as GMT increases beyond 3°C, the number of people at risk of hunger increases steadily.

All the studies indicated tremendous variation in regional results for agriculture, which we do not show here. One generalisation is that, in most cases, the existing disparities in crop production between developed and developing countries were estimated to increase. These results are a reflection of longer and warmer growing seasons at high latitudes, where many developed countries are located, and shorter and drier growing seasons in the tropics, where most developing countries lie. Results in mid-latitude regions are mixed.

On the whole it appears uncertain whether global agriculture experiences benefits, adverse impacts, or virtually no effect for increases in GMT up to approximately 3–4°C. The four studies, however, estimated increasing adverse global impacts beyond this level. These observations are consistent with the broader literature on agriculture, which shows crop yields declining beyond a global mean increase of approximately 3°C (see Gitay et al., 2001). This phenomenon reflects the knowledge that grain crops, which represent the vast majority of crop revenues, have temperature thresholds beyond which yields decline. Farmers can grow crops at higher latitudes and altitudes to maintain production within optimal temperature ranges, but eventually this geographical shifting cannot compensate

[2] Arnell et al. (2002), in a study that in part provides the basis for Parry et al. (2001), presented results that are quite similar to these. Though the method is nearly identical to that employed by Parry et al. (1999), the results rely on a single GCM, as do those for the other sectors that Arnell et al. (2002) and Parry et al. (2001) modelled. Because of the similarity of results, method, and the reliance on a single GCM, we do not discuss either study in detail here but do touch on some aspects of the general method in the Conclusions and Discussion section.

for higher temperatures. It is also possible that future research and development will result in crops with even higher temperature thresholds. However, if climate change results in increased climate variance, greater threat of pests, substantial reductions in irrigation supply, or less efficient or effective adaptation, the threshold could be lower.

3.3. Water resources

We examined four studies that assessed the potential impacts of climate change on water resources: Alcamo et al. (1997); Arnell (1999); Vörösmarty et al. (2000), and Döll (2002).

Arnell (1999) used a macro-scale hydrological model to simulate river flows across the globe, and then calculated changes in national water resource availability. These changes were then used with projections of future national water resource use to estimate the global effects of climate change on water stress, and to estimate the number of people living in countries that experience water stress or in counties that experience a change in water stress. Vörösmarty et al. used a water balance model that is forced offline with GCM output to estimate the number of people experiencing water stress. Alcamo et al. (1997) used a global water model that computes water use and availability in each of 1162 watersheds, taking into account socio-economic factors that lead to domestic, industrial, and agricultural water use as well as physical factors that determine supply (runoff and ground water recharge). Some aspects of the model's design and data came from the IMAGE integrated model of global environmental change (Alcamo et al., 1994). The study relied on two GCMs for physical and climatic input. Alcamo et al. (1997) estimated the scarcity of water by means of a criticality index, which combines the criticality ratio (ratio of water use to water availability) and water availability per capita in a single indicator of water vulnerability. Döll (2002) used a global model of irrigation requirements, reporting changes in net irrigation requirements. Net irrigation was computed as a function of climate and crop type, with climatic input generated by two transient climate models.

The results from the water studies are far less consistent and conclusive than those of other sectors. Fig. 3, based on Arnell's (1999) results, indicates the changes in the number of people living in countries experiencing water stress with increasing temperature. Arguably, it is impacts to this category of people that are most important. However, establishing what constitutes water stress is ultimately a rather subjective step. Nevertheless, there is not much change in water stress by this measure between the 2020s and the 2080s (increases in GMT of roughly 1°C and 3°C, respectively). As might be expected, the relatively wetter HadCM2 model

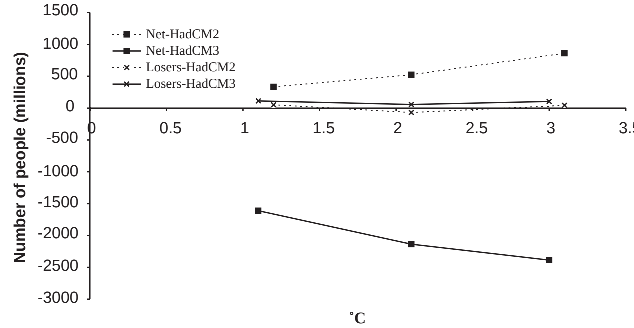

Fig. 3. Water resources: impacts on water resources as a function of temperature. Panel e shows two measures of the impact of climate change on users of water resources, both derived from Arnell (1999). Data represented by an "*x*" are changes in the number of people in countries using more than 20% of their water resources. This measure focuses on impacts on those people who live in or near a state of water stress. Data represented by a solid square are the difference between the total population in countries where water stress increases and countries where water stress decreases. This measure looks at the number of winners versus losers regardless of the whether they live in a state of water stress or not. Data source: Arnell (1999). In both cases results are shown as averages for the decades of the 2020s, 2050s and 2080s.

predicts fewer people living in water stressed conditions. Panel e also shows the difference between the total population of countries where stress increases and the total population of countries where stress decreases. This measure gives a better sense of the total number of winners versus losers (though one could argue that the gains of winners do not really offset the losses of losers) with regard to changes in water stress, regardless of arbitrary thresholds. The trend is still ambiguous, since one model predicts net loss (HadCM2) and another predicts net gain (HadCM3). Counter to what one might expect, it is the drier model (HadCM3) that predicts a larger population of people in countries where water stress decreases. This is driven mainly by the fact that in the HadCM2 scenario, stress increases in the populous countries of India and Pakistan, while in the HadCM3 scenario, stress decreases in these countries. In both figures, the results are sensitive to large countries flipping from one situation to another. Regionally, the countries where climate change has the greatest adverse impact on water resource stress are located around the Mediterranean, in the Middle East, and in southern Africa. Significantly, these countries are generally least able to cope with changing resource pressures. Overall, these results indicate the importance of the regional distribution of precipitation changes to estimates of water resource impacts.

Vörösmarty et al.'s (2000) results indicate that climate change has little effect globally on water resource pressure. The effects of increased water demand due to population and economic growth eclipse changes due to climate. Here again it is important to note regional changes, which are masked by global aggregates.

Vörösmarty et al. predicted significant water stress for parts of Africa and South America. This is offset by estimated decreases in water stress resulting from climate change in Europe and North America. In general, climate change produces a mixture of responses, both positive and negative, that are highly specific to individual regions. Of course, there is only a limited amount of climate change by 2025, the date at which the Vörösmarty et al. analysis ended.

Alcamo et al. (1997) presented results that highlight the impact of climate change on future water scarcity for only one point in time, 2075, and for one of the two GCMs that the study employed. The study suggested that, globally, overall annual runoff increases and water scarcity is somewhat less severe under climate change. In a world without climate change, 74% of the world's population is projected to live in water scarce watersheds by 2075. However, with climate change, this figure is reduced to 69%. These results are consistent with those of Vörösmarty et al. (2000), suggesting that climate change is not the most important driver of future water scarcity. Growth in water use due to population and economic growth is the decisive factor. Though Alcamo et al. (1997) suggested that climate change may ameliorate water scarcity globally, regionally the picture is quite different. Some 25% of the earth's land area experiences a decrease in runoff in the best guess scenario (which combines moderate estimates of future intensity and efficiency of water use) according to Alcamo et al. (1997), and some of this decrease is estimated to occur in countries that are currently facing severe water scarcity. The Alcamo et al. (1997) results also point to the possibility that industry will supersede agriculture as the world's largest user of water.

Döll's (2002) results mirror those of Vörösmarty et al. When cell-specific net irrigation requirements are summed over world regions, increases and decreases of cell values caused by climate change average out. Irrigation requirements, however, increase in 11 out of 17 of the world's regions by the 2020s, but not by more than 10%. By the 2070s, increases occur in 12 of these regions, 10 of which also show an increase in the 2020s.

The relationship between water resources and climate change appears to be inconclusive. A clear trend did not appear in the studies, perhaps because of the methods used and because of inconsistent changes in regional precipitation patterns across the climate models. Averaging world regions or even countries presents many problems. The water basin is the critical unit for analysis of water resources. Changes in one part of a basin, such as increased or decreased runoff, will affect other parts of the basin. Such changes have little effect outside the basin unless one basin feeds into another or is connected to another via water transport infrastructure. Since basins and transport infrastructure do not necessarily conform to national borders, an analysis based on estimating a uniform change for individual countries may not capture realistic impacts on water resources.

A second critical reason why we do not see a clear relationship between increases in GMT and effects on water resources appears to be inconsistent estimates of changes in regional precipitation. An increase in GMT would increase global mean precipitation. However, the nature of regional changes in precipitation is quite uncertain and varies considerably across climate models. Differences in precipitation patterns from one climate model to another are probably more important than differences in mean temperature in terms of effect on estimates of impacts on water resources. Beyond this, the impacts on water resources are extremely complicated and can depend on such factors as how water is consumed, the ability to adjust uses, legal and institutional constraints, and the capacity to build or modify infrastructure.

Nevertheless, an argument can be made that adverse impacts to the water resources sector will probably increase with higher magnitudes of climate change.[3] This argument is based on two considerations. One is that water resource infrastructure and management are optimised for current climate. The more future climate diverges from current conditions, the more likely it is that thresholds related to flood protection or drought tolerance will be exceeded with more frequency and with greater magnitude than they currently are. The second consideration is that more severe floods and droughts are expected to accompany higher magnitudes of climate change. Some regions might benefit from a more hydrologically favourable climate, but it seems unlikely that the majority of the world's population would see improved conditions, especially since systems are optimised for current climate.

3.4. Human health

The effects of climate change on human health could find expression in numerous ways. Some health impacts would doubtless result from changes in extremes of heat and cold or in floods and droughts. Others might result indirectly from the impacts of climate change on ecological or social systems. Assessing the impacts of climate change on human health in any comprehensive way is extraordinarily difficult. Health impacts are

[3] Parry et al. (2001) and Arnell et al. (2002) both presented results that suggest steadily increasing numbers of people at risk of water shortage as global mean temperature increases, for both the 2050s and the 2080s. However, they considered only the numbers of people already living with water stress who would experience an increase in stress due to climate change. This approach neglects those people for whom water stress decreases and in general neglects the impacts, negative or positive, on those people who do not currently live in water stressed countries. Essentially, this study considered losers only and provided no sense of net impacts.

complex and owe their causes to multiple factors. They may lead to increases in morbidity and mortality for some causes and decreases for other causes. Vulnerability will differ from one population to another and within every population over time (McMichael et al., 2001). In general, there is insufficient literature to begin to form other than the most rudimentary conclusions concerning overall health impacts.

Malaria transmission is the only impact category with several studies with good global and temporal coverage. The impacts of climate change on vector-borne disease are unlikely to be limited to malaria (dengue and schistosomiasis are likely possibilities), but malaria might be representative of how climate change may affect the risks of vector-borne diseases in general. Consequently, we focused on three studies that assessed the possible impacts of climate change on the global transmission of malaria: Martin and Lefebvre (1995), Martens et al. (1999), and Tol and Dowlatabadi (2002).

Climate change is likely to lead to increased water stress and deteriorate water quality in some areas, which in turn might well increase the incidence of water-borne diseases. Several studies suggest a correlation between average annual temperature and the incidence of diarrhoeal diseases. However, these studies are limited in the range of temperatures they examine or are not yet published. We present the results of one such study, Hijioka et al. (2002).

We also examined Tol's (2002a, b) results of how mortality is influenced directly by changes in temperature, both high and low.

3.4.1. Malaria

Martin and Lefebvre (1995) used a relatively simple model of malaria that predicts potential transmission, which occurs when environmental conditions are favourable at the same time and place to both malaria parasites and malaria vectors. The model also makes prediction based on endemicity, distinguishing between seasonal and perennial transmission. They presented results in terms of area of potential transmission.

Martens et al. (1999) is based on a model of malaria that is part of the MIASMA model (e.g., Martens et al., 1997; Martens, 1999). This model is more sophisticated than that of Martin and Lefebvre in that it includes estimates of the distribution of 18 different malaria vectors, species-specific relationships between temperature and transmission dynamics, and a more realistic approach on malaria endemicity (epidemics versus year-round transmission). Results were presented in terms of changes in the number of people at risk of malaria infection.

Tol and Dowlatabadi (2002) transformed the results from several studies predicting risk of malaria transmission to actual mortality by assuming that the current regional death tolls from malaria increase as the risk of potential transmission increases with temperature. They also explored the importance of access to public health services on malaria mortality by assuming a linear relationship between regional per capita income and access to public health services and relating the latter to reductions in mortality.

The studies portrayed an increase in health risks with increasing temperature. Martin and Lefebvre (1995; Fig. 4, panel a) suggested that a global increase of seasonal potential malaria transmission zones is caused by the encroachment of seasonal zones on perennial ones and by the expansion of seasonal malaria into areas formerly free of malaria. The increase in area of potential transmission in all malarious zones seems to be linear and increasing with temperature.

The results from Martens et al. (1999) are shown in Fig. 4, panel b. The trends depict additional people at risk for *vivax* and *falciparum* malaria, for both the

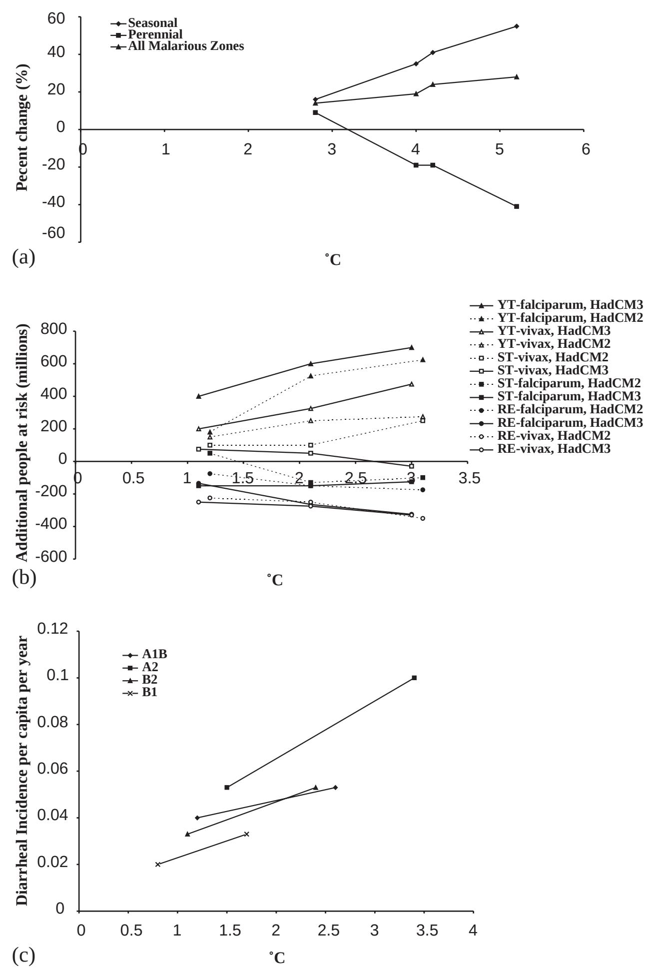

Fig. 4. Human health: (a) percent change in the extent of malaria transmission as a function of temperature, by the type of transmission. Data source: Martin and Lefebvre (1995). (b) Additional people at risk for malaria as a function of temperature, by type of transmission and parasite species. Data source: Martens et al. (1999). (c) Diarrheal incidence per capita per year, shown for four different SRES scenarios. Data source: Hijioka et al. (2002). Align these graphs by *x*-axis 0.

HadCM2 and HadCM3 models and for different types of transmission. Year-round transmission appears to increase linearly with temperature for both types of malaria parasite. However, the risk of epidemics is reduced and in both cases decreases gradually with temperature. It is more difficult to draw conclusions about seasonal transmission, though for *falciparum*, at least, risk also seems to decrease with rising temperature. In both cases, these measures risk missing potential increases in the actual disease burden. The portion of the year during which transmission can occur might increase, but if the increase is not enough to trigger a change in risk category, as defined in the study, this increase will not register. The results could, however, indicate an expansion of year-round transmission at the expense of seasonal and epidemic transmission, coupled with an expansion at the fringes of malarious zones, mostly likely in the form of epidemic transmission potential.

Aggregating these various modes of transmission and types of malaria is not straightforward.[4] For instance, an increase in risk of year-round transmission is not necessarily more serious than an increase in risk of seasonal transmission. In fact, the reverse could well be true in many locations. Populations exposed to malaria year-round often develop a higher immunity than do those exposed less frequently (Gubler et al., 2001). Arguably, one could simply sum the number of people at risk for malaria, regardless of endemicity or variety of parasite. Though this clearly mixes types of risk, it would provide some crude indication of how the total number of people exposed to malaria might change with climate. Doing this in panel c would yield an increasing trend, suggesting that the number of people at risk of malaria over the next century does increase. This could be the case. However, such aggregation is inadvisable given that different sorts of malaria risk are likely to have different implications for actual mortality and the pitfalls in interpretation that result from aggregation.

Tol and Dowlatabadi (2002) took the approach of converting risk of potential transmission to mortality, which allows for aggregation across different endemicities smoothly. However, Tol and Dowlatabadi provided results of mortality as a function of only time and not temperature. They did, though, show that by the last decade of the century, global mortality from malaria is reduced to virtually zero as a result of economic growth and presumably better access to public health services. The effect of socio-economic change appears to overwhelm the negative effect of climate change alone.

3.4.2. Water-borne disease

Hijioka et al. (2002) developed a statistical model to explain the current incidence of diarrhoeal disease in 13 world regions. The model relies on two explanatory variables, water supply coverage and annual average temperature. It simultaneously accounts for the reduction in water-borne diarrhoeal incidence resulting from improvements in the water supply coverage and related sanitary conditions in developing countries (due to increasing income) and for the increase in diarrhoeal incidence resulting from the proliferation of pathogens and promotion of putrefaction due to increased temperatures in both developing countries and developed countries. They presented global results for two time slices, 2025 and 2055, for each of the four scenarios they considered. Results, as a function of temperature, are shown in Fig. 4, panel c. While there are only two data points for each scenario, these plots indicate that higher temperatures are accompanied by a higher incidence of diarrhoeal disease.

3.4.3. Heat- and cold-related mortality

Tol (2002a) estimated the effects of climate change on both heat- and cold-related mortality. With rising temperatures, one would expect a decrease in cold-related mortality and an increase in heat-related mortality. Tol extrapolated from a meta-analysis conducted by Martens (1998) that showed the reduction in cold-related cardiovascular deaths, the increase in heat-related cardiovascular deaths, and the change in heat-related respiratory deaths in 17 countries in the world. Tol concluded that, for the world as a whole, reduction in cold-related mortality is greater than the increase in heat-related deaths initially. He predicted reductions in mortality peak at rather moderate changes in temperature by 2050. From that point on, marginal increases in temperature result in mortality increases. His results are characterised by rather large uncertainty, but suggest that as temperatures continue to rise, reductions in cold-related mortality will be less significant while increases in heat-related mortality will dominate.

[4] Parry et al. (2001) and Arnell et al. (2002) presented results for additional millions of people at risk of malaria for both the 2050s and the 2080s that suggest a steadily increasing trend between temperature increases of 0° and 3°C. These studies relied on a method and socio-economic assumptions that are quite similar to those of Martens et al. (1999). Both studies looked at the total additional population living in an area where the potential for malaria transmission exists. The two studies differed from Martens et al. only in how they aggregated results. Results were aggregated across different types of risk, as defined by seasonality of transmission. Total aggregate results included the populations of all areas that experience an increase in potential transmission and where the duration of the transmission season is at least 1 month per year. Furthermore, results were presented for only one malaria parasite, *falciparum*, and much of the increase that was indicated is for what is most likely epidemic transmission in developed countries, where public health infrastructure makes it unlikely that such a risk would be realised as a significant disease burden.

3.4.4. Main health findings

Based on our review of the literature and related analysis, we conclude that health risks are more likely to increase than decrease as GMT rises. While the results from the malaria studies we considered do not point to an unambiguous increase in risk as temperatures rise (in fact, underlying principles suggest that high temperatures might increase or decrease the survival of vectors and pathogens they transmit; see Gubler et al., 2001), they do suggest that such an increase in transmission may be more likely than not. However, this may not necessarily translate to an increase in mortality or morbidity. Hijioka et al. (2002) also demonstrated that the threat of water-borne diseases may increase as climate changes. The limited results we examined for heat-related mortality suggest that, eventually, as temperatures rise so will total mortality. While demographic and sociological factors play a critical role in determining disease incidence (Gubler et al., 2001), many of these maladies are likely to increase in low latitude countries in particular (heat stress will most likely increase in mid- and high latitudes as well). Low latitude nations have some of the highest populations in the world, tend to be less developed, and thus have more limited public health sectors. It is possible that nations in low latitudes will develop improved public health sectors, but the speed and uniformity of such development are in doubt. Taking all these considerations into account, it seems more likely that mortality and morbidity will rise than fall. We characterise the relationship between human health and climate change as one of increasing damages.

3.5. Energy

We reviewed one study, the only global study of which we are aware, that estimated the effects of climate change on the demand for global energy: the energy sector analysis of Tol's (2002b) aggregate study. Tol followed the methodology of Downing et al. (1996), extrapolating from a simple country-specific (United Kingdom) model that relates the energy used for heating or cooling to degree days, per capita income, and energy efficiency. Climatic change is likely to affect the consumption of energy via decreases in the demand for space heating and increases in demand for cooling. Tol, following Downing et al., hypothesized that both relationships are linear. Economic impacts were derived from energy price scenarios and extrapolated to the rest of the world. Energy efficiency is assumed to increase, lessening costs. Tol analysed energy use through 2200 but did not report how temperature changes over this period, so we cannot associate a particular level of net benefits with a given temperature.

According to Tol's (2002b) best guess parameters, by 2100, benefits (reduced heating) are about 0.75% of gross domestic product (GDP) and damages (increased cooling) are approximately 0.45%. The global savings from reduced demand for heating remain below 1% of GDP through 2200. However, by the 22nd century, they begin to level off because of increased energy efficiency. For cooling, the additional amount spent rises to just above 0.6% of GDP by 2200. Thus throughout the next two centuries, net energy demand decreases. Despite the results at 2200, it is reasonable to assume that at high enough levels of temperature change, the increased spending on cooling will eventually dominate the savings from reduced expenditure on heating.

We are highly confident that global energy use will eventually rise as global mean temperature rises, but we are not certain about whether a few degrees of warming will lead to increased or decreased energy consumption. With higher temperatures, demand for heating decreases and demand for cooling increases. One can imagine that a curve relating energy demand to mean global temperature might be "U" shaped. An important question is whether we are already to the right of the low point of such a curve, in which case global energy consumption will rise with higher GMT, or whether we are still on the portion of the curve that foretells decreasing demand (left of the low point), in which case global energy consumption will first decline and then eventually rise as GMT increases. Tol's analysis suggested that we can still look forward to reductions in total consumption. However, Mendelsohn's (2001) analysis of the United States found that energy costs will increase even with an approximate 1°C increase in GMT. Since the United States consumes about one-fourth of global energy, this may be an indication that global energy demand will increase immediately as temperatures rise. Thus, based on the limited literature, we were unable to determine the effective shape of the damage relationship we face.

3.6. Terrestrial ecosystem productivity and change

Climate change could potentially affect a number of physical and biological processes on which the health and composition of terrestrial ecosystems depend. Changes in these ecosystem processes could in turn affect an equally diverse set of services on which people rely, some of which are considered elsewhere in this paper (agriculture, forestry, and biodiversity). However, a significant portion of the overall value of terrestrial ecosystems could be related to non-market sorts of goods and services or services not associated with concrete goods in any sense. Biodiversity is an example of such a good. These are difficult values to measure, and no global studies of which we are aware have attempted to quantify the impacts of climate change on terrestrial ecosystems by estimating the values of these sorts of services. Instead we focused on studies that examined the general health and productivity of terrestrial ecosystems and presumably their ability to deliver a wide range of services.

We examined two studies of the effects of climate change on terrestrial ecosystems, White et al. (1999) and Cramer et al. (2001), both of which model net ecosystem productivity (NEP), net primary productivity (NPP), and total carbon. A third study, Leemans and Eickhout (in this issue), looks at shifts in the extent of ecosystem types with climate change.

Fig. 5 depicts the global changes in NPP and NEP as function of GMT change from White et al. (1999). NPP increases fairly steadily until the 2050s, or about 2°C, at which point it begins to level off. This global trend reflects an increase in NPP of northern forests in response to warming and increased atmospheric CO_2 concentrations and in some places precipitation. However, NPP decreases in southern Europe, the eastern United States, and many areas of the tropics. NEP, the difference between NPP and heterotrophic respiration, represents the net flux of carbon from between land and the atmosphere. Decreases in NEP appear after about 1.5°C of warming. The decreases in NEP were associated with the decline or death of tropical or temperate forests. Thus, White et al. predicted a growing terrestrial carbon sink at lower temperatures, but a collapse and reversal of this sink at higher temperatures. Leemans and Eickhout, citing a 1999 study by Cramer et al., suggest that this reversal occurs somewhere between 2°C and 3°C. Similarly, Cramer et al. (2001) indicated that the terrestrial carbon sink begins to level off by 2050 and decreases by the end of the century.

It is reasonable to expect that the relationship between increased GMT and ecosystem productivity is parabolic. Higher atmospheric carbon dioxide concentrations will favourably affect plant growth and demand for water (although change in growth may not result in increased biomass in natural, unmanaged, systems). Higher temperatures, particularly if accompanied by

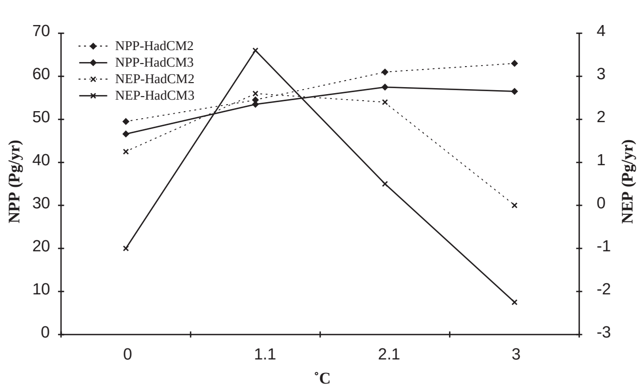

Fig. 5. Terrestrial ecosystems: change in net primary productivity and net ecosystem productivity as a function of temperature. Results are shown as averages for the decades of the 2020s, 2050s and 2080s. Data source: White et al. (1999).

increasing precipitation, could also initially be favourable for plant growth. Eventually, the increased growth will peak and then decline as the carbon dioxide fertilisation effect begins to saturate at higher CO_2 concentrations (approximately 600–800 ppm for C_3 plants; Rosenzweig and Hillel, 1998). Additionally, higher temperatures exponentially increase evapotranspiration, thus increasing water stress to vegetation. In summary, there are biophysical reasons to expect vegetation productivity to increase with a small rise in global mean temperature, then peak, and eventually decline. The modelling results of the White et al. (1999) and Cramer et al. (2001) studies are consistent with this hypothesis.

Leemans and Eickhout more generally addressed large-scale compositional impacts on ecosystem and landscape patterns. They looked at how climate change would affect the distribution of ecosystems and NEP over the planet, for GMT changes of 1°, 2°, and 3°C. Climate change was obtained through the standardised IPCC pattern scaling approach (Carter et al., 2001).

The simulated shifts in ecosystems that Leemans and Eickhout reported show rising impacts with larger temperature increases. A 1°C warming alters more than 10% of all ecosystems (89.6% of all ecosystems are stable). These ecosystem impacts increase with increasing temperatures. At 2°C and 3°C, 16% and 22% of all terrestrial ecosystems change, respectively. There are of course large differences in specific ecosystems. And, as the authors point out, net changes in ecosystem extent often obscure the disappearance of ecosystems. Additionally, not all changes are alike. The authors characterised changes in extent as negative, positive, or neutral, depending upon the succeeding vegetation. Positive changes are typically characterised by a shift that results in increased NEP and theoretically provides more opportunities for managing ecosystem services. Neutral changes are those where current ecosystems are replaced by new ecosystems with similar productivity characteristics but composed of different species. Negative changes are those that depict a decline in use opportunities and a release of carbon. The analysis indicated that positive and neutral NEP impacts increase with climatic warming. However the authors are quick to point out, these changes are based on climatic potential, not actual dynamics. There is substantial evidence suggesting that many ecosystems cannot keep pace with rapid climate change and might deteriorate, resulting in rapid carbon loss to the atmosphere. In fact, Leemans and Eickhout's results indicate that with an increase of 3°C over the course of the current century, only 30% of impacted ecosystems might be able to adapt. It is entirely possible then that the potentially positive effects the model results seem to suggest, might in reality fail to materialise, at least at higher rates of climate change. Indeed, impacts could well be negative.

This result is generally consistent with those of the two ecosystem productivity studies we examined although Leemans and Eickhout's analysis goes further to examine multiple indicators of ecosystem impacts. However, they did not examine GMTs beyond 3°C.

3.7. Forestry

We present temperature correlated results from one study of the impacts of climate change on global forestry, Sohngen et al. (2001). Other global studies of the forest sector exist (e.g., Perez-Garcia et al., 2002), but do not generally present results as a function of temperature or do not evaluate the long-term economic consequences of impacts on forests.

Sohngen et al. estimated impacts of climate change on world timber markets. Their analysis was designed to not only capture the climate change driven ecological impacts on forest growth and distribution but also provide insight into how landowners and markets adjust and adapt to global climate change.

Sohngen et al. detailed changes in consumer and producer surplus under several scenarios that describe how timber species might move across landscapes in response to changing climatic conditions. Sohngen et al. also explored, via sensitivity analyses, the effect of higher or lower interest rates, assumptions about the ability of forests to expand, and future competition for plantation sites in the tropics. The general results were the same. Global timber supply increases and prices decline under all scenarios and assumptions. Global net surplus increases, consumers benefit because prices are lower, high latitude producers tend to lose, and low to mid-latitude producers tend to gain. Fig. 6 depicts results for timber production. Global yields clearly increase over time because of two factors. First, climate change increases the annual growth of merchantable timber by increasing NPP. Second, the BIOME3 model predicts a pole-ward migration of more productive species, which tends to increase the area of these more productive species.

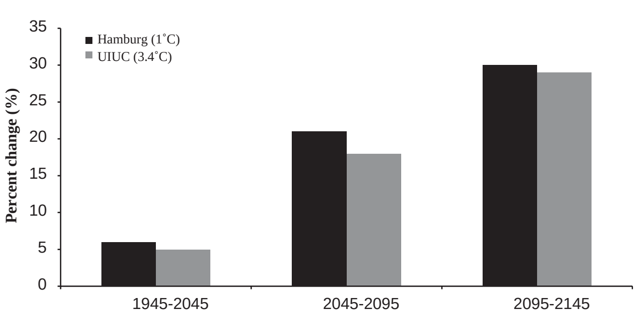

Fig. 6. Forestry: percentage change in timber production for three 50-year time periods. Panel j, based on Sohngen et al. (2001) shows the change in timber production for three time periods and two different GCMs. Both GCMs were subjected to a doubling of CO_2, where equilibrium was assumed to occur at 2060. Data source: Sohngen et al. (2001).

However, while global forest yields rise, output seems to be only loosely coupled to global temperature increases. Both the Hamburg and UIUC GCM models show comparable gains in yield at each time step, though their underlying global temperature predictions are quite different (approximately 1°C versus 3.4°C). The higher temperature scenario, UIUC, predicts slightly lower benefits than the low temperature Hamburg scenario.

We would expect the economic results for forestry to roughly track biophysical changes in terrestrial vegetation. When growth is estimated to increase, production should rise as well. If growth decreases at some point, production should too. This is also the case in agriculture. We are limited in our conclusions by a lack of forestry studies that correlate results to temperature. Furthermore, the complexities of lags resulting from decadal-long harvesting times make it difficult to draw conclusions about the impacts of rising temperature on forestry. Also, the slow dispersal times of unmanaged forest ecosystems could well limit their adaptive capacity, and reduce projected benefits. However, it does appear that everything else equal, both climate change scenarios in Sohngen et al. result in benefits, albeit the scenario with higher GMT has slightly lower benefits. This suggests, but does not confirm, that the relationship between GMT and global forest production is parabolic. However, without the benefit of studies that look at wider range of climate changes, we were unable to draw a more definitive conclusion.

3.8. Terrestrial biodiversity

We examined two studies that inform speculation regarding the impacts of climate change on global terrestrial biodiversity: Halpin (1997) and Leemans and Eickhout (in this issue).

Estimating the impacts of climate change on the global abundance and distribution of biodiversity is challenging. Halpin hypothesised that the survival and distribution of terrestrial plant and animal species depend on the distribution of the climates on which they depend. Specifically, he estimated the percentage of biosphere reserves that might experience a significant change in "ecoclimatic class" as well as the global average change for all terrestrial areas. A change from a current ecoclimate class to a different class was interpreted as a significant climate impact for a reserve site. The analysis predicted sites where the climatic change falls within the existing climatic range of the bioreserve and sites where the projected change exceeds the current range. It was presumed that biodiversity in reserves that have a change in climate will be threatened.

Leemans and Eickhout took a similar approach, examining ecosystem change in nature reserves. They also assume that when current vegetation disappears, it is highly unlikely that the original protection objectives of reserves can be met.

Fig. 7, derived from Halpin's (1997) analysis, displays the frequency with which biosphere reserves and terrestrial areas in general experience a change in ecoclimatic class as a function of temperature. With the exception of a hitch around a 4°C change, presumably due to the difference in precipitation between GISS and GFDL, the trend is generally increasing and linear. While the GCM scenarios project major changes in the distribution of ecoclimate classes at a global scale, the more important point is that the frequency of ecoclimatic impacts on reserve areas is generally higher than the global averages. Halpin suggested a fairly straightforward explanation. The global distribution of reserves has a northern spatial bias because of the greater abundance of land mass at mid- and high northern latitudes and the fact that northern industrialised nations maintain more reserve sites. This bias coincides with the larger magnitude of climate impacts in high latitude regions projected by the GCMs that Halpin used. This produces higher rates of climate change for reserve sites than the average for terrestrial areas.

Leemans and Eickhout conclude that ecosystem changes in nature reserves are similar to the more general patterns they report, but by definition are negative, given that the chief goal of reserves is the conservation of current ecosystems. With a 3°C increase in GMT, half of all nature reserves will be incapable of upholding their original conservation objectives. In fact, negative impacts are likely to increase faster in reserves given their uneven distribution and tendency to be located in exposed or sensitive biomes, both of which reduce their inherent adaptive capacity.

It seems highly likely that larger increases in GMT this century will result in more losses of biodiversity for two reasons. Many species may be able to tolerate a limited level of change in climate, but at higher levels of change, tolerance thresholds will be exceeded. Higher GMTs also mean faster rates of change in climate, which will exceed the ability of increasing numbers of species to adapt. In addition, the threat to biodiversity from climate is much larger when considered in conjunction with the pressures of development. Habitat fragmentation and pollution, among other factors, already threaten many species. In combination with climate change, the loss could be larger (Peters and Lovejoy, 1992). We are highly confident that biodiversity will decrease with increasing temperatures; what is uncertain is whether the relationship between higher GMT and loss of biodiversity is linear or exponential.

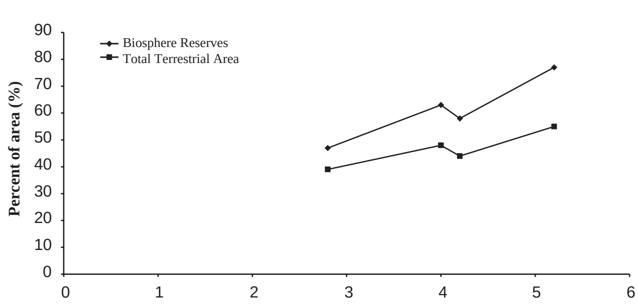

Fig. 7. Terrestrial biodiversity: percent change in ecoclimatic classes for biosphere reserves compared to global average. Data source: Halpin (1997).

3.9. *Marine ecosystem productivity*

We examined one study that analysed changes in the production of marine ecosystems due to climate change: Bopp et al. (2001). They investigated how climate change might affect marine primary production (production by marine plants, including phytoplankton and seaweeds). As with terrestrial ecosystem productivity, this one metric is limited and does not directly translate into fish productivity or changes in biodiversity. However, any changes in primary production would propagate up the marine food web and consequently indicate the possible effects of climate change on productivity of marine ecosystems in general.

Both biogeochemical models employed by Bopp et al. predicted similar responses to climate change. At $2xCO_2$ they predicted a 6% global decrease in export production (that portion of marine primary productivity that is transported below 100 m) and showed opposing changes in the high- and low-latitude regions. Climate induced changes in the ocean decreased export production by 20% in the low latitudes, but increased it by 30% in the high latitudes. The results in the economically important fisheries region of the equatorial Pacific indicate that export production decreased by 5–15%. In general, changes in production are driven by reduced nutrient supplies in the low latitudes and an increased light efficiency in the high latitudes, leading to a longer growing season there. Both changes result from increased stratification in the upper ocean. Results were not reported for lower levels of climate change, so it is not possible to determine if global export production declines with smaller increases in global mean temperature.

With only one study containing few data points, it is difficult to draw conclusions about how marine ecosystem productivity is related to increased GMT. Clearly, at some point, increasing GMT leads to reduced marine ecosystem productivity. It is reasonable to assume that further increases in GMT lead to further decreases in productivity, but we are uncertain about the relationship between GMT and marine ecosystem productivity for temperature changes less than those considered by Bopp et al.

3.10. Aggregate

We examined two studies that analysed the aggregate global impacts of climate change across a number of sectors and expressed results in monetary terms (as a percentage of economic output): Tol (2002a, b) and Nordhaus and Boyer (2000). Other aggregate studies focus on market impacts only or are limited in geographic scope (e.g., Mendelsohn and Neumann, 1999; Mendelsohn et al., 2000a, b; and Mendelsohn, 2003).

Tol's (2002a, b) study considered impacts of climate change on agriculture, forestry, species, ecosystems, and landscapes, sea level rise, human health, energy consumption, and water resources. He conducted both a static analysis of the impacts of a 1°C change in global temperature on the present situation and a dynamic estimate of the potential impacts over the 2000–2200 period, taking into account the vulnerability of regions to impacts (changes in population, economies, and technology).

Tol's results showed that the impacts of climate change can be positive as well as negative, depending on the sector, region, or time period being combined. The impact on overall welfare depends on how one aggregates results. Aggregating results across regions, even when results are expressed in monetary fashion as they were in Tol's analysis, is problematic. Tol aggregated static results both as simple sums and in an equity weighted fashion, where average income by region determines the weighting factors. The simple sum results in a 2.3% increase in income globally, but risks unduly emphasising impacts on the rich, whose marginal utility of income is apt to be less than that of the poor. The equity weighted sum reduces this figure to 0.2% of income. The picture of dynamic results was also mixed (Tol, 2002b). There are both positive and negative impacts for different regions at different points in time. Dynamic results were not aggregated globally.

Nordhaus and Boyer's (2000) aggregate analysis relied on an integrated model. The model took a willingness-to-pay (WTP) approach, estimating the insurance premiums different societies are willing to pay to prevent climate change and its associated impacts, particularly catastrophic events. Parameters were estimated based on existing studies, modification of existing results, guessing, and survey results. The Nordhaus and Boyer analysis is unique among aggregate studies in its attempted inclusion of non-market and potential catastrophic impacts as well as market impacts. The study estimated impacts in agriculture, sea level rise, other market sectors, health, non-market amenities, human settlements and ecosystems, and catastrophic events.

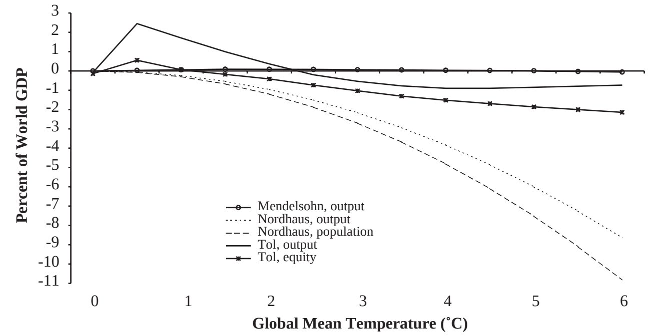

Fig. 8. Aggregate: estimated aggregate global damages. Data sources: Mendelsohn and Schlesinger (1997), Nordhaus and Boyer (2000), and Tol (2002b).

Nordhaus and Boyer presented aggregate damage curves for regions and by weighted summation, where weights are based on population or projected 2100 regional output. The global average of damages for a 2.5°C warming is 1.5% if weighted by output or 1.9% if weighted by 1995 population. For most countries, market impacts are small in comparison to the willingness to pay to avoid the possibility of potential catastrophic impacts. The large uncertainty associated with these WTP estimates implies that there is great uncertainty associated with the overall results.

The few studies on aggregate impacts of climate change consistently estimated that there will be damages beyond approximately 2–3°C of increase in GMT (Fig. 8). Damages were estimated to continue increasing at higher increases in temperature. This is consistent with aggregate studies that focus on market impacts as well (e.g., Mendelsohn and Neumann, 1999; Mendelsohn et al., 2000a). Disagreement among the studies concerns what happens for smaller increases in GMT. Some studies showed net benefits for a small amount of warming, while Nordhaus and Boyer showed damages at such levels. Thus, the aggregate studies did not present consistent results concerning the shape of the damages curve, but did consistently show increasing damages at higher magnitudes of climate change. For a few degrees of increase in mean global temperature, aggregate impacts appear to be uncertain.

4. Conclusions and discussion

Table 1 summarises the patterns in the studies we examined by sector. It is clear that the relationships between GMT and impacts are not consistent across sectors. Some sectors exhibit increasing adverse impacts with increasing GMT. Since the data reported in the studies are limited, we were generally unable to determine if these relationships are linear or exponential.

Table 1
Summary of sectoral damage relationships with increasing temperature

Sector	Increasing adverse impacts[a]	Parabolic	Unknown	Confidence
Agriculture		X[b]		Medium/low
Coastal	X			High
Water			X	
Health	X[c]			Medium/low
Terrestrial ecosystem productivity		X		Medium
Forestry		X[d]		Low
Marine ecosystems	X[e]			Low
Biodiversity	X			Medium/ high
Energy			X	
Aggregate			X	

[a] Increasing adverse impacts means there are adverse impacts with small increases in GMT, and the adverse impacts increase with higher GMTs. We are unable to determine whether the adverse impacts increase linearly or exponentially with GMT.
[b] We believe this is parabolic, but predicting at what temperature the inflection point occurs is difficult due to uncertainty concerning adaptation and the development of new cultivars.
[c] There is some uncertainty associated with this characterisation, as the results for the studies we examine are inconsistent. On balance, we believe the literature shows increasing damages for this sector.
[d] We believe this is parabolic, but with only one study it is difficult to ascertain temperature relationship, so there is uncertainty about this relationship.
[e] This relationship is uncertain because there is only one study on this topic.

Some sectors are characterised by a parabolic relationship between temperature and impacts, and for the others the relationship is indecipherable. The table also indicates our subjective level of confidence in our conclusions regarding the nature of the relationship between GMT and impacts in those sectors where a determination is possible.

We did not aggregate damages across sectors explicitly, given that our primary concern was to determine the general shape of damage functions and assess the consistency of results within sectors. Given this focus on deciphering trends in sectoral impacts, the magnitude of those impacts is less important in this analysis. In fact, in many of the sectors we examined, the results vary widely both within studies, from scenario to scenario or GCM to GCM, and between studies. Furthermore, given that different studies seldom use precisely the same scenarios and make precisely the same socio-economic baseline assumptions, aggregating even within a sector is fraught with difficulty. Aggregation across sectors is hindered by the fact that impacts in different sectors are expressed in different metrics.

Since the different sector studies did not demonstrate a consistent relationship over the full range of temperature increase they collectively examine, and since we did not aggregate across sectors explicitly, it is not possible to draw a definitive conclusion about whether impacts, when taken together, generally increase or take on a parabolic form over this range.

That said, one consistent pattern is that by an approximate 3–4°C increase in global mean temperature, all of the studies we examined, with the possible exception of those on forestry, suggest adverse impacts. It appears likely that as temperatures exceed this range, impacts in the vast majority of sectors will become increasingly adverse. Although many studies point to substantive impacts below this temperature level, there is no consistency; in some cases they are negative and in others positive.

4.1. Uncertainties

A number of important sources of unresolved uncertainty underlie this conclusion. We do not believe that these uncertainties cast significant doubt on the basic shape of damage curves we characterize. However, if resolved they might well warrant a reconsideration of our identification of 3–4°C as the point beyond which damages are adverse and increasing and would shed more light on the nature of impacts at temperatures below this range. Many of the studies we considered did not appropriately account for, or simplified, important factors that could influence our conclusion. For instance:

- The bulk of the current generation of global impact studies assumes only a change in average climate and does not address changes in climate variance. Changes in variance are plausible and have already been observed to some extent (Timmerman et al., 1999; Easterling et al., 2000). More impact studies are attempting to model the impacts of changes in variance at the sector level (for example in agriculture, Chen et al., 2001; Rosenzweig et al., 2002), but results are too preliminary to determine how the totality of impacts in a sector would be affected.[5]
- Impact studies tend also to make simple assumptions about adaptation. It is difficult to predict exactly how affected parties will react. Smit et al. (1996) and West and Dowlatabadi (1999), among others, point out the complexities involved in adaptation. Adaptations in response to rapid changes in climate or changes in variance are likely to be ever more difficult to predict (Callaway, in this issue). Additionally, much existing

[5] Chen et al. (2001) and Rosenzweig et al. (2002) are for the United States alone. They showed increased variability reducing the magnitude of gains in US agriculture, but not necessarily resulting in net losses.

consideration of adaptation fails to account for the cost of these adaptations.

- The speed and nature of economic and technological development also raise important questions about the vulnerability of tomorrow's systems to climate change. Tol and Dowlatabadi (2002) concluded that large increases in income could substantially reduce the vulnerability of people in developing countries to induce malaria mortality by climate change.
- Many impact studies do not look beyond the 21st century. It is highly likely that climate will continue changing into the 22nd century and even beyond (Watson and The Core Writing Team, 2001). For systems in which there is long-term inertia, such as the climate-ocean system, long-term consequences of different levels of increase in GMT on sectors such as coastal resources may be underestimated.
- Furthermore, very few studies consider potential catastrophic changes in the climate system, such as shutdown of the ocean's thermohaline circulation, and concomitant impacts, and thus may underestimate long-term adverse impacts associated with particular increases in GMT.
- Finally, there are important linkages between many of the sectors that we considered. For example, impacts to agriculture and water resources are linked in areas where agriculture is irrigated (Hanemann, forthcoming). These linkages might result in exacerbation or, in some cases, amelioration of the impacts we report.

4.2. Recommendations for research

The resolution of many of these uncertainties may have to wait for the development of more sophisticated impact models or improved projections of climate change. However, our analysis points to several steps that might be taken now to improve the usefulness and credibility of the current generation of impact studies:

- Efforts should be made to improve methods for expressing impacts in natural sectors (i.e., terrestrial ecosystem productivity, marine ecosystems, biodiversity) in metrics that are meaningful to policy makers. Numerous studies predict how ecosystems might respond to warming. However, measures such as NEP or NPP are abstruse for policy makers, and they significantly hamper efforts at aggregating impacts across sectors. What is missing is a sense of how important these responses might be, to what extent they might be managed, and ultimately the extent to which people care. Much the same can be said for social sectors that are non-market in character (e.g., human health and amenities).
- Impacts across sectors can be compared confidently and easily only if studies share a consistent approach to the development and application of climate scenarios, socio-economic baselines, timeframes, and methods of analysis. Looking across studies that rely on different GCMs can be tricky, even when the globally averaged climate scenarios they produce are similar. Country specific temperatures and precipitations especially can vary tremendously across models. Single sector studies that rely on a single GCM are less useful than those that use a suite of models. While different GCMs can give a sense for the range of potential impacts within a single sector or in the context of a global impact model (Mendelsohn et al., 2000a), cross-sector evaluation of impacts generated by different regional climate scenarios is problematic. Similarly, when different socio-economic baselines are used it can be difficult to determine to what extent the results are affected by these assumptions. Furthermore, methods of analysis must be transparent. For instance, when impacts are measured in terms of people affected, studies should provide disaggregated results that allow analysts to draw their own conclusions about net impacts, in line with the policy questions they seek to inform.
- Most existing studies are structured in a way that makes it difficult to translate results into policy insight. More studies should be designed with some explicit thought given to questions regarding mitigation or adaptation. Parry et al. (2001), which developed multi-sector impact assessments for several mitigation scenarios, provides a good methodological model. It also takes a consistent approach to socio-economic baselines and timeframes.
- While most of the studies we examined highlight regional results, more discussion should be devoted to the process and validity of spatial aggregation used to obtain global results. In many cases it may be reasonable that one region's gains offset another's losses (e.g., agriculture). In others, it may be better to leave results in regional form (e.g., water resources).
- Addressing sectors for which there are no global impact estimates or for which information is limited is important. Climate change impacts on tourism and recreation, and amenity values, could all involve substantial societal impacts and monetary values. In addition, there are a number of sectors for which only some impacts have been assessed or for which there are a limited number of global studies. This is particularly the case for energy and terrestrial and marine ecosystems, including terrestrial animals and fisheries. There is also limited information about impacts on developing countries in general.
- Based on this survey, there are several sensitive sectors where our understanding of the relationship between impacts and changes in GMT should be improved, most notably water resources and human health. Even small magnitudes of climate change

could adversely affect many hundreds of millions of people who are afflicted with climate sensitive health impacts each year or who lack adequate and safe water supplies. On the other hand, development could substantially reduce the vulnerability of these sectors to climate change in the future (Tol et al. and Yohe —both in this issue). To better understand the global consequences of climate change, it would help to clarify the relationship between climate change and these two sectors in particular.

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