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published in
Mitigation and Adaptation Strategies for Global Change
2007

DOI (link to publisher)
10.1007/s11027-007-9097-2

document version
Publisher's PDF, also known as Version of record

Mitig Adapt Strat Glob Change (2007) 12:741–753
DOI 10.1007/s11027-007-9097-2

ORIGINAL ARTICLE

The double trade-off between adaptation and mitigation for sea level rise: an application of FUND

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Received: 7 May 2006 / Accepted: 30 May 2006 / Published online: 9 May 2007

Abstract This paper studies the effects of adaptation and mitigation on the impacts of sea level rise. Without adaptation, the impact of sea level rise would be substantial, almost wiping out entire countries by 2100, although the globally aggregate effect is much smaller. Adaptation would reduce potential impacts by a factor 10–100. Adaptation would come at a minor cost compared to the damage avoided. As adaptation depends on socio-economic status, the rank order of most vulnerable countries is different than the rank order of most exposed countries. Because the momentum of sea level rise is so large, mitigation can reduce impacts only to a limited extent. Stabilising carbon dioxide concentrations at 550 ppm would cut impacts in 2100 by about 10%. However, the costs of emission reduction lower the avoided impacts by up to 25% (average 10%). This is partly due to the reduced availability of resources for adaptation, and partly due to the increased sensitivity to wetland loss by adaptation.

Keywords Adaptation · Mitigation · Sea level rise

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1 Introduction

Many people phrase climate policy's basic trade-off as that between mitigation and adaptation (e.g., Barbier and Pearce 1990; Nordhaus 1991; Schelling 1992; Parry et al. 1998). If we would mitigate more, climate change and its impacts are lower and we would have to adapt less. Optimal climate policy would balance the marginal costs of emission reduction and the marginal damage costs of climate change (Nordhaus 1992; Manne et al. 1995; Tol 1999), itself a trade-off between adaptation and residual damage (Smith and Lenhart 1996; Fankhauser et al. 1999; Mendelsohn 2000).[1] However, if we would mitigate more, we would have less resources left for adaptation, and climate change impacts may be higher. This argument is often overlooked, although eloquently made by Schelling (1992, 1995), and demonstrated by Tol and Dowlatabadi (2001) and Tol (2002c). This paper revisits this argument, focussing on sea level rise.

Although my previous papers on this issue focussed on health, sea level rise may be the best place to demonstrate the double trade-off between adaptation and mitigation. Like health care, the standards of coastal protection rise with economic growth, perhaps rapidly so. However, the ocean reacts much more slowly to greenhouse gas emission reduction than does the atmosphere. This implies that slowing sea level rise in this century requires a larger and more expensive effort than slowing climate change. Therefore, there may be few short-term coastal benefits from mitigation, while the income effect of mitigation on coastal adaptation may be larger and more immediate.[2]

To my knowledge, this subject has not been studied. Most studies of the impacts of sea level rise are classic impact studies, estimating the effects in one or more scenarios (Hoozemans et al. 1993; Baarse 1995; Leatherman and Nicholls 1995; Nicholls et al. 1995, 1999; Nicholls 2002, 2004). Only Nicholls and Lowe (2004) estimate the difference between a business-as-usual and an emission reduction scenario. However, Nicholls and Lowe (2004) disregard the effect of deep emission cuts on economic growth, implicitly assuming that emission abatement is cost-less.

The literature on adaptation and mitigation is, of course, broader than the few papers quoted above. Direct and quantitative comparisons of adaptation and mitigation strategies are rare, however. There are a number of reasons for this. The benefits of mitigation fall on all sectors in all countries, whereas adaptation is specific to sectors and often countries. The clients of adaptation and mitigation studies are different as well. Adaptation studies should be targeted at local managers of natural resources, whereas mitigation studies should be aimed at national and international decision makers in energy, transport, and agriculture. Finally, adaptation and mitigation consider different time-scales. This all makes a direct comparison of adaptation and mitigation hard and, in most cases, meaningless. In Tol (2003), I further elaborate this. In this paper, I compare the avoided impacts due to mitigation on the one hand to the increased vulnerability due to mitigation costs on the other hand.

[1] I phrase climate policy in terms of cost–benefit analysis. There are of course also other ways of interpreting policy. However, adaptation and mitigation are necessarily substitutes in climate policy, regardless of how one looks at it. Note that adaptation cannot fully replace mitigation or vice versa; the climate policy portfolio should contain both adaptation and mitigation. Finally, note that adaptation is impossible for some systems, particularly some ecosystems; there, mitigation is the only alternative.

[2] Note that the same trade-off holds for the long-term, but that mitigation is more potent and adaptation, perhaps, less effective. Note also that impact analyses seldom go beyond 2100, even though sea level rise will not stop then.

The paper proceeds as follows. In the next section, the model used, version 2.8n of FUND, is presented. Section 3 discusses the scenarios. Section 4 shows estimates of the impacts of sea level rise. Section 5 analyses how impacts change with emission reduction. Section 6 concludes.

2 The model

The model used is version 2.8n of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND[3]). Version 2.8n is different in many ways from previous versions. However, in this paper, only coastal impacts are used, and these are as described in Tol (2002a, b). The essentials are given below. Version 2.8n differs from version 2.8 (Link and Tol 2004) in that version 2.8n runs at its maximum spatial resolution, that is, 207 countries; version 2.8 has only 16 regions.

Essentially, FUND2.8n consists of a set of exogenous scenarios based on which impacts are calculated. The model runs from 1995 to 2100 in time steps of 5 years. The scenarios are the SRES scenarios, as implemented by the IMAGE2 model (IMAGE Team 2002). The scenarios concern the rate of population growth and economic growth, carbon dioxide concentrations, global mean temperature and sea level rise.

The climate impact module is based on Tol (2002a, b). The following impact categories of climate change are considered: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems. In this paper, only sea level rise impacts are used. The impacts of sea level rise include dryland loss, wetland loss, protection costs, and forced migration.

These impacts interact with one another. For example, if a piece of dryland is fully protected, no dryland will be lost, but the costs of protection will be high, and the adjacent wetland may be inundated. The total impact of sea level rise depends on the adaptive policy chosen. Consequently, the estimated damage depends strongly on the projected policy. For instance, IPCC CZMS (1991) uses the ad hoc rule that all dryland with a population density above 10 people per square meter will be protected while Fankhauser (1994, 1995) and Yohe et al. (1995, 1996) employ models, which choose the economically optimal level of protection. The difference can be substantial.

The coast length of all countries in the world was taken from the Global Vulnerability Assessment (GVA) (Hoozemans et al. 1993), an update of work earlier done for the IPCC (IPCC CZMS 1990). Other sources, such as the proceedings of the 1993 World Coast Conference (Bijlsma et al. 1994), Nicholls and Leatherman (1995a, b) and Fankhauser (1995), use (occasionally widely) different estimates of the length of the coast of particular countries. However, the length of a coast depends on the measurement procedure. The GVA is based on an internally consistent, globally comprehensive data-set. Therefore, the GVA is used here.

Wetland losses for a 1 m sea level rise were taken from the GVA and, where available, replaced with results from country studies as reported by Bijlsma et al. (1996) plus Nicholls and Leatherman (1995a, b). The reasons are: (i) the GVA is a desk study which occasionally shows signs of the great haste of its preparation; (ii) the country studies use local data; and (iii) land lost because of sea level rise is more obviously estimated than coast length. Bijlsma et al. (1996), however, only report wetland losses in the absence of

[3] Monosyllabic acronyms rule.

coastal protection. The GVA reports wetland losses both with and without coastal protection; the country-specific ratio between the two was used to derive wetland losses with protection according to Bijlsma et al. (1996). Without coastal protection, following the GVA, wetland loss is assumed to be linear in sea level rise. The resulting wetland model is crude and based on incomplete and older data. However, for want of a better model, it is used here.

Dryland losses are not reported in the GVA, but they are by Bijlsma et al. (1996). The GVA reports people-at-risk, which is the number of people living in the one-in-1000-year flood plain, weighted by the chance of inundation. Combining this with GVA's coastal population densities, area-at-risk results. The exponential of the geometric mean of the ratio between area-at-risk and land loss for the 18 countries in Bijlsma et al. (1996) was used as a correction factor to derive land loss for all other countries. Following the GVA, without protection, dryland loss is assumed to be linear in sea level rise.

The monetary value of a loss of one square kilometer of dryland was on average \$4 million in OECD countries in 1990 (cf. Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at \$2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income.

Coastal protection against sea level rise is based on cost–benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze. The level of protection is derived by Fankhauser (1994):

$$L = \min\left\{0, 1 - \frac{1}{2}\left(\frac{\mathrm{PC} + \mathrm{WL}}{\mathrm{DL}}\right)\right\}$$

L is the fraction of the coastline to be protected. PC is the net present value of the protection if the whole coast is protected. The GVA reports average costs per year over the next century. PC is calculated assuming annual costs to be constant. This is based on the following. Firstly, the coastal protection decision makers anticipate a linear sea level rise. Secondly, coastal protection entails large infrastructural works, which last for decades. Thirdly, the considered costs are direct investments only, and technologies for coastal protection are mature.

Throughout the analysis, a pure rate of time preference, ρ, of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of the economy, g. The net present costs of protection PC thus equal

$$\mathrm{PC} = \sum_{t=1}^{\infty}\left(\frac{1}{1+\rho+g}\right)^t \mathrm{PC}_a = \frac{1+\rho+g}{\rho+g}\mathrm{PC}_a$$

where $\mathrm{PC_a}$ is the average annual costs of protection.

WL is the net present value of the wetlands lost due to full coastal protection. Land values are assumed constant, reflecting how much current decision makers care about the non-marketed services and goods that get lost. The amount of wetland lost is assumed to increase linearly over time. The net present costs of wetland loss WL follow from

$$\mathrm{WL} = \sum_{t=0}^{\infty} t\left(\frac{1}{1+\rho+g}\right)^t \mathrm{WL}_0 = \frac{1+\rho+g}{(\rho+g)^2}\mathrm{WL}_0$$

where WL_0 denotes the value of wetland loss in the first year.

DL denotes the net present value of the dryland lost if no protection takes place. Land values are assumed to rise at the same pace as the economy grows. The amount of dryland lost is assumed to increase linearly over time. The net present costs of dryland loss DL are

$$DL = \sum_{t=0}^{\infty} t\left(\frac{1}{1+\rho+g}\right)^t DL_0 = \frac{(1+g)(1+\rho+g)}{\rho^2} DL_0$$

where DL_0 is the value of dryland loss in the first year.

Another effect associated with dryland loss is that the people who used to live on the washed land are forced to move elsewhere. Forced migration may well be one of the most pronounced impacts of sea level rise (Myers and Kent 1995), considering the fact that people tend to cluster in deltas and near shores (Vellinga and Leatherman 1989). Emigration estimates follow from multiplying the projected loss of drylands with the country-average population density. The value of emigration is set to be 3 times the per capita income (Tol 1995, 1996). This implies that migration is linear in land lost and population growth, while migration costs are linear in land loss, population growth and per capita income growth. The same is true for (the value of) dryland lost. Hence, the dynamics of migration are similar to the dynamics of other, less controversial impacts. Migration results are therefore not shown.

3 Scenarios

The population scenario used is IPCC SRES A1/B1 scenario (Nakicenovic and Swart 2001) as implemented in the IMAGE 2.2 model (IMAGE Team 2002). The IMAGE model has population projections for 17 world regions. Population growth was assumed to be the same for all countries within a region. The A1/B1 scenario has moderate population growth. The world population peak at 8.7 billion people in 2055, and falls to 7.0 billion in 2100.

The scenario for per capita income is the IPCC SRES A1B scenario, again as implemented in IMAGE. Per capita income growth within a region is assumed to be uniform. Economic growth is fairly rapid. Japan is the slowest grower, seeing its per capita income quadruple over the century, an average annual growth of 1.3%. The fastest grower is South Asia, seeing its per capita income increase by a factor of 180, an average annual growth of 5.1%. This paper does not evaluate the SRES scenarios.

Using the population and economic scenarios, as well as the corresponding scenarios on technological progress, the full FUND model, version 2.8,[4] was used to generate scenarios of climate change and sea level rise. In this scenario, the sea rises by 66 cm (cf. Church and Gregory 2001).

As a stabilisation scenario, CO_2 concentrations are kept below 550 ppm. The stabilisation scenario was implemented in the full FUND 2.8 model. Atmospheric stabilisation slows sea level rise, but only by about 10 cm in 2100. Later gains are much larger. Atmospheric stabilisation requires greenhouse gas emission reduction, which reduces economic growth. For this scenario, per capita income is about 3% lower in 2100 than in the baseline scenario. This is well within the range of projected income losses (Weyant 2004). The same value is applied everywhere.

[4] That is, the version with 16 regions rather than 207 countries.

I use only one scenario, without any sensitivity analyses, to keep the exposition simple and short. Although, the numbers would be different for different scenarios, the qualitative results are likely to be similar. Yohe and Schlesinger (2000) study the sensitivity of the impacts of sea level rise, including adaptation, to alternative emissions futures.

4 Costs and benefits of adaptation

Figure 1A shows dryland loss, as a fraction of the 2000 area, per country in 2000, 2025, 2050, 2075, and 2100. Coasts are assumed to be unprotected. Exposure differs by 7 orders of magnitude. The most exposed countries are the Maldives (77% land loss in 2100), Micronesia (21%), Macau (18%), Vietnam (15%) and Bangladesh (10%). Exposure increases over time. In the case of the Maldives, the projected land loss is 13% in 2025, 29% in 2050, 51% in 2075 and 77% in 2100.

Figure 1C shows the annual costs of dryland loss, as a percentage of GDP. As dryland value is assumed to be linear in income density, the rank order is the same. The most exposed countries are the Maldives (122% of GDP in 2100), Micronesia (12%), Macau (10%), Vietnam (8%) and Bangladesh (5%). The economic exposure grows less fast than the physical exposure, as the rate of the sea level rise is faster than the rate of economic growth. In the case of the Maldives, the costs of land loss are 19% of GDP in 2025, 32% in 2050, 55% in 2075, and 122% in 2100.

Figure 2A shows wetland loss, as a fraction of the 2000 area, per country in 2000, 2025, 2050, 2075, and 2100. Coasts are assumed to be unprotected. Exposure differs by 3 orders of magnitude. The most exposed countries are the Benin (62% wetland loss in 2100), Congo (Kinshasa) (55%), Cameroon (52%), Bangladesh (46%) and Pakistan (46%). Exposure increases over time, but at a decelerating rate as wetlands disappear entirely. In the case of Benin, the project wetland loss is 9% in 2025, 22% in 2050, 40% in 2075 and 62% in 2100.

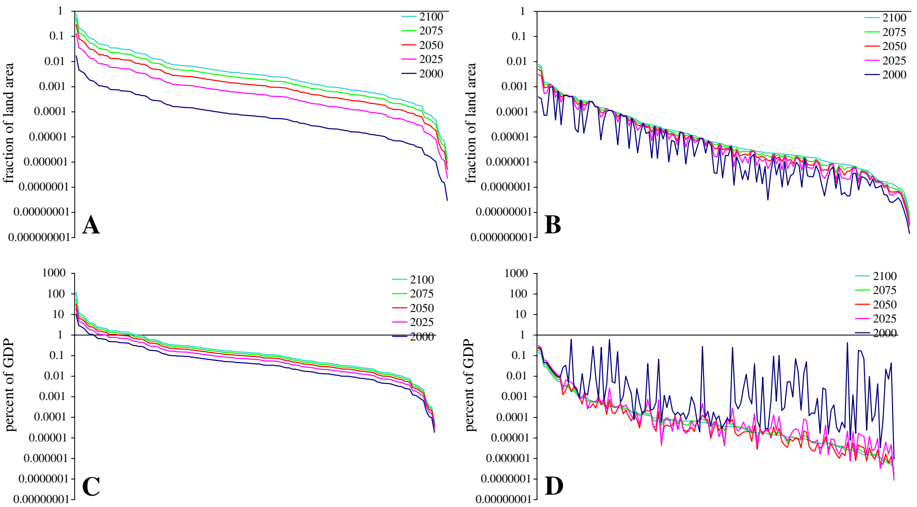

Fig. 1 Loss of dryland (fraction of total area in 2000; top panels **A** and **B**) and its annual value (percent of GDP; bottom panels **C** and **D**) without protection (left panels **A** and **C**) and with (right panels **B** and **D**). Countries are ranked as to their values in 2100

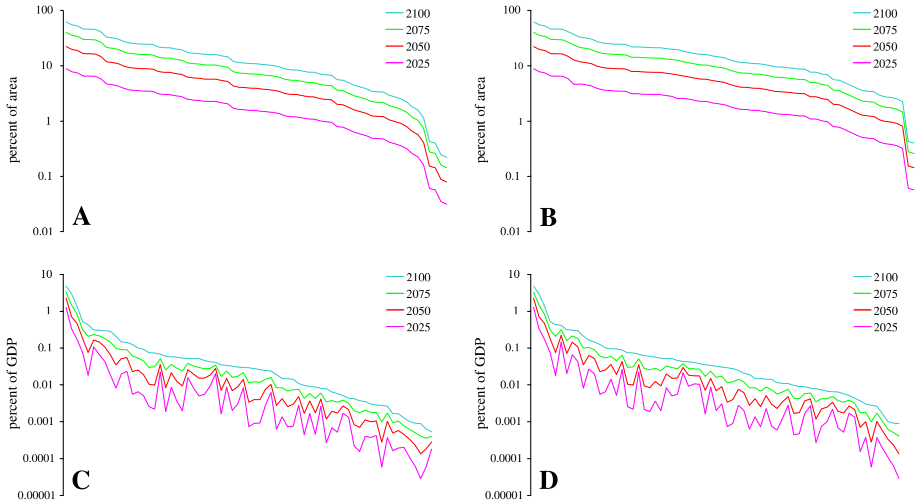

Fig. 2 Loss of wetland (fraction of total area in 2000; top panels **A** and **B**) and its annual value (percent of GDP; bottom panels **C** and **D**) without protection (left panels **A** and **C**) and with (right panels **B** and **D**). Countries are ranked as to their values in 2100

Figure 2B shows the annual costs of wetland loss, as a percentage of GDP. Exposure differs by 6 orders of magnitude. As wetland value is non-linear, the rank order is different than for wetland area. The most exposed countries are the Bahamas (4.8% of GDP in 2100), Papua New Guinea (3.0%), Belize (1.4%), Malaysia (0.5%) and Senegal (0.4%). The economic exposure grows faster than the physical exposure, as people grow richer while wetlands get scarcer, both of which drive up the value of wetlands. For the Bahamas, the value of wetland loss amounts to 1.3% of GDP in 2025, 2.3% in 2050, 3.3% in 2075 and 4.8% in 2100.

Figure 3 shows the optimal protection level for those countries, which would lose land otherwise; for the other countries, the optimal protection level is zero. The model predicts that almost all countries would have full coastal protection as of 2025. There are a few rank reversals through time, as some countries grow faster than others. The least protected countries in 2100 are Kiribati (74% of the vulnerable coast line protected), New Caledonia (94%), Fiji (96%), New Zealand (96%) and Sweden (96%). Figure 3 also shows the annual costs of protection, expressed as a percentage of GDP. Relative protection costs differ

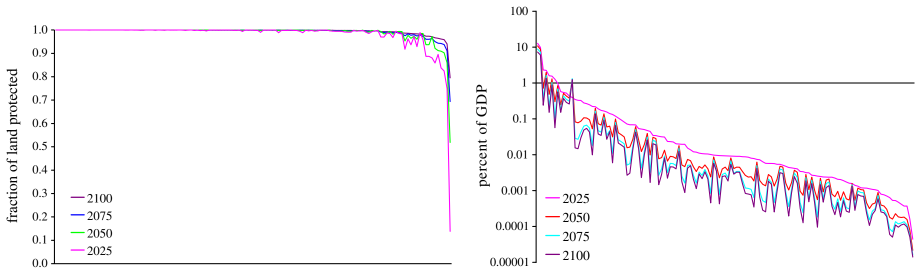

Fig. 3 Protection level (fraction of coast protected; left panel) and the annual costs of protection (percent of GDP; right panel). Countries are ranked as to their protection level

seven orders of magnitude. The countries, which pay most for coastal protection are Micronesia (0.36% of GDP in 2100), Palau (0.30%), Tuvalu (0.07%), Kiribati (0.06%) and the Marshall Island (0.04%). Costs fall over time. In the case of Micronesia, protection costs are 0.63% in 2025, 0.54% in 2050, 0.44% in 2075 and 0.36% in 2100. A cursory comparison of protection costs and the costs of dryland loss indicates why protection levels are so high.

Figure 1B shows dryland losses with optimal protection. At the maximum end, land loss falls by two orders of magnitude; at the minimum end, by one order of magnitude. Whereas without protection (exposure), the rank order of countries is preserved over time, this is not the case with protection (vulnerability). The relative vulnerabilities of countries change as some grow faster than do others. In 2100, the most vulnerable countries are Micronesia (7.6% land loss), Palau (6.4%), Kiribati (1.5%), Tuvalu (1.4%), and Mozambique (1.3%). Over time, physical vulnerability rises. For Micronesia, land losses are 3.1% of land area in 2025, 5.0% in 2050, 6.4% in 2075 and 7.6% in 2100. This is because land loss in irreversible and cumulative.

Figure 1D shows the annual costs of dryland loss, as a percentage of GDP, with optimal coastal protection. At the maximum end, economic loss falls by more than two orders of magnitude; at the minimum end, by three orders of magnitude. As with physical vulnerability, the rank order of economic vulnerability is not preserved over time; this is more pronounced for physical than for economic vulnerability, though. In 2100, the most vulnerable countries are Micronesia (0.15% of GDP), Palau (0.12%), Kiribati (0.03%), Tuvalu (0.03%), and the Marshall Islands (0.02%). Over time, economic vulnerability falls, in contrast to physical vulnerability. In the case of Micronesia, the value of land losses is 0.30% of GDP in 2025, 0.23% in 2050, 0.18% in 2075 and 0.15% in 2100. This is because protection levels increase.

Figure 2C shows wetland losses with optimal protection. Wetland losses increase in some 20 countries. Wetlands suffer most from coastal protection in Liberia (21% land loss due to coastal protection in 2100; Liberia is seventh on the list of most vulnerable countries), Puerto Rico (18%), St Lucia (18%), Jamaica (18%) and South Africa (11%). All other countries suffer losses of less than 5% of wetland area. Whereas without protection (exposure), the rank order of countries is preserved over time, this is not the case with protection (vulnerability). The relative vulnerabilities of countries change as some have higher protection than do others and some wetlands are more susceptible to coastal squeeze than are others. However, the top 5 most vulnerable countries remains the same, and the time profile does not change substantially.

Figure 2D shows the annual costs of wetland loss, as a percentage of GDP. People suffer the greatest welfare losses due to wetland losses because of coastal protection in Denmark (0.11% of GDP; Denmark is sixth on the list of most vulnerable countries), Antigua and Barbuda (0.04%), Liberia (0.04%), Ireland (0.04%) and Honduras (0.03%). As with physical vulnerability, the rank order of economic vulnerability is not preserved over time; this is more pronounced for economic vulnerability. The top 5 most vulnerable countries does not change, however, and the time profile is hardly different.

5 Costs and benefits of mitigation

Figure 4 shows the difference in protection levels because of emission reduction (sea level rise plus slower economic growth) for the world and for Kiribati, where this effect is largest. The effect of lower sea level rise alone is too small to depict. Because of emission

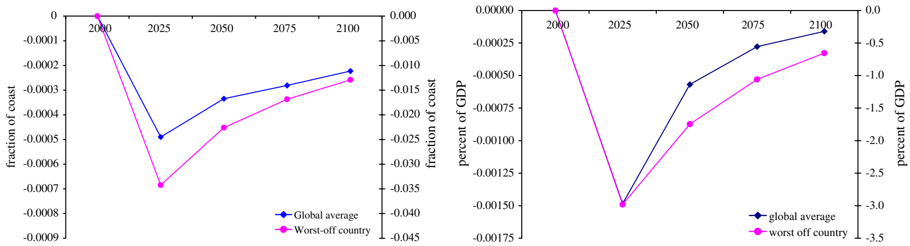

Fig. 4 The effects of emission reduction (that is, lower sea level rise and the corresponding emission reduction costs) on coastal protection for the world and for Kiribati (left panel) and on the annual costs of coastal protection for the world and for Micronesia (right panel); the global numbers are displayed on the left axes, the country numbers on the right axes

reduction, 4% less of the coastline of Kiribati would be protected; the difference is smaller still for the world. Figure 4 also shows the difference in annual protection costs because of emission reduction for the world and for Micronesia, where this effect is largest. The effect of emission reduction coincides with the effect of lower sea level rise, as the effect of slower economic growth alone is too small to depict. Cost savings are less than 0.16% GDP in Micronesia, and much less than that for the world. The differences are zero in 2000, by construction. The differences are maximum in 2025. For protection levels, this is because more and more countries choose close to full protection as time progresses, and stick to that policy regardless of small deviations in sea level or development. For protection costs, the same pattern is observed because protection costs grow not as fast as does the economy.

Figure 5 displays dryland losses and its annual costs in 2100 according to the business as usual scenario and the emission reduction scenario; Fig. 5 also shows the difference. A stringent emission reduction scenario as considered here cuts land loss and its costs by about 10%. This is because the momentum of sea level rise is so large. The greatest beneficiaries, both in terms of area and value, are Micronesia, Palau, Kiribati, Tuvalu and the Marshall Islands. Unsurprisingly, this is also the list of countries most vulnerable to sea level rise.

Figure 6 shows the difference in dryland loss and its annual costs because of emission reduction and because of lower sea level rise alone for the world and for Japan, where the difference due to adding the costs of emission reduction is largest (in relative terms). As seen in Fig. 5, emission reduction reduces the impacts on drylands. However, lower sea

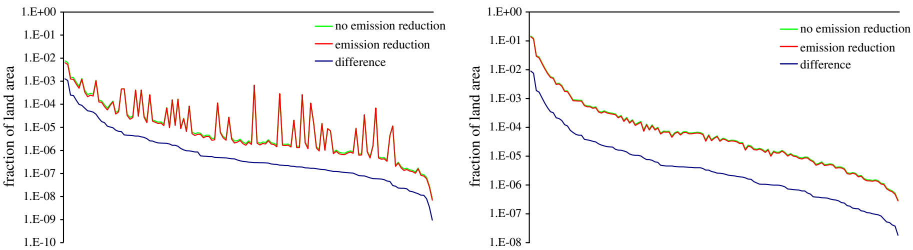

Fig. 5 The dryland loss (fraction of 2000 land area; left panel) and its annual costs (percent GDP; right panel) in 2100 according to the business as usual scenario and the emission reduction scenario. The difference is also shown. Countries are ranked according to the difference

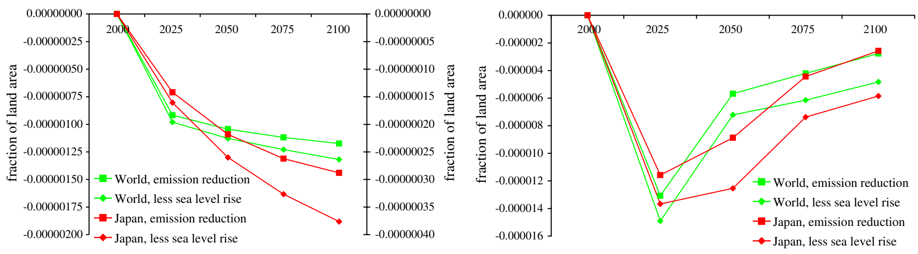

Fig. 6 The effects of lower sea level rise alone and of emission reduction (that is, lower sea level rise and reduced economic growth) on dryland loss (left panel) and its annual costs (right panel) for the world (left axis) and for Japan (right axis)

level rise has a positive effect, while the costs of emission reduction has a negative effect. For the world as a whole, emission reduction costs take away 11% of the benefits of lower sea level rise in 2100; in Japan, this number is 23%. In general, emission reduction costs take away a larger (smaller) share of the benefits of reduced sea level rise in richer (poorer) countries because the loss of wetlands due to coastal protection is of greater (smaller) concern, making the optimal protection level more (less) sensitive to economic growth.

Figure 7 displays wetland losses and its annual costs in 2100 according to the business as usual scenario and the emission reduction scenario; Fig. 7 also shows the difference. A stringent emission reduction scenario as considered here cuts wetland loss and its costs by about 10%, the same order of magnitude as dryland loss avoided. This is because the impacts are (assumed to be) essentially linear in sea level rise. The greatest beneficiaries in terms of wetland area are Benin, Congo (Kinshasa), Cameroon, Bangladesh and Pakistan; in terms of wetland value, the greatest beneficiaries are the Bahamas, Papua New Guinea, Belize, Malaysia and Senegal. Again, this coincides with the list of countries most vulnerable to sea level rise.

Figure 8 shows the difference in wetland loss and its annual costs because of emission reduction and because of lower sea level rise alone for the world and for Australia (wetland area) and Papua New Guinea (wetland value), where the difference due to adding the costs of emission reduction is largest (in relative terms). As seen in Fig. 7, emission reduction reduces the impacts on wetlands. However, lower sea level rise has a positive effect, while the costs of emission reduction has a negative effect. For the world as a whole, the effect of emission reduction costs on wetland area saved is negligible; in Australia, the number is 0.2% in 2100. For the world, the effect of emission reduction costs on wetland value saved is 5%; in Papua New Guinea, this is 17% in 2100.

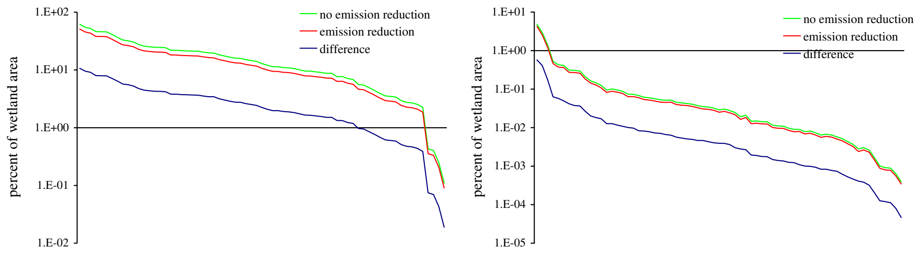

Fig. 7 Wetland loss (fraction of 2000 wetland area; left panel) and its annual costs (percent GDP; right panel) in 2100 according to the business as usual scenario and the emission reduction scenario. The difference is also shown. Countries are ranked according to the difference

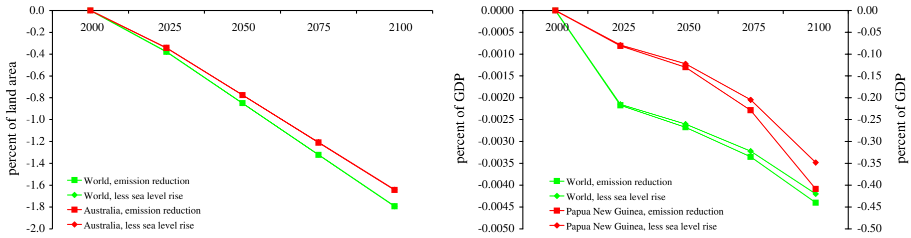

Fig. 8 The effects of lower sea level rise alone and of emission reduction on wetland loss (left panel) and its annual costs (right panel) for the world (left axis) and for Australia (wetland area; left axis) and Papua New Guinea (wetland costs; right axis); note that the costs of emission reduction have no discernible effect on wetland loss

6 Discussion and conclusion

Four scenarios are systematically compared. The first scenario is a scenario with economic and population growth, climate change and sea level rise, but no adaptation. The second scenario has adaptation. The benefits of adaptation, in this case dike building, are substantial in terms of land loss prevented and economic damage avoided. The costs of adaptation are smaller than the benefits. Adaptation costs include the costs of dike building, but also the wetlands squeezed between the rising sea and dikes. Because adaptation depends on such things as population density and per capita income, vulnerability (with adaptation) does not correspond one-to-one with exposure (without adaptation).

In the third scenario, the level of the sea rises more slowly, corresponding to a stabilisation of CO_2 concentrations at 550 ppm. Although the emission reductions required for this are substantial, the momentum in climate change and sea level rise is too large to avoid more than 10% of the impacts on wetlands and drylands. Protection levels are hardly affected, but dikes need to be less high, which implies savings on costs.

In the fourth scenario, the costs of emission reduction are also included. Because economic growth is less, countries are less able and less willing to defend themselves against the rising sea. The costs of emission reduction take away an average of 10% (a maximum of 25%) of the benefits of emission reduction for drylands, and an average of 5% (a maximum of 20%) for wetlands. These numbers suggest that one cannot estimate the benefits of emission reduction (as in the third scenario) without also considering the costs of emission reduction.

This analysis was done with a single model, a single set of parameters, and a single baseline scenario. An analysis of the sensitivities and uncertainties is obviously needed but beyond the scope of this paper. Sea level rise impact studies, including this one, often stop in 2100, even though the sea will continue to rise substantially after that. Future work will need to address that. The qualitative insight—that emission reduction affects the impacts of sea level rise through the climate as well as through the economy—is independent of parameters, scenarios, and models. The estimated quantity would differ.

That basic insight shows that adaptation and mitigation are not just alternative policy options for climate change. If mitigation is higher, less adaptation is needed, but there is also less adaptation possible or desirable. Adaptation and mitigation strategies should be studied together.

Acknowledgements Comments by three anonymous referees and discussions with Robert Nicholls helped improve this paper. The CEC DG Research Fifth Framework Programme through the DINAS-Coast project

(EVK2-2000-22024), the US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation for Environmental Protection provided welcome financial support. All errors and opinions are mine.

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