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ORIGINAL ARTICLE

Costs and benefits of differences in the timing of greenhouse gas emission reductions

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Abstract Most modelling studies that explore long-term greenhouse gas mitigation scenarios focus on cost-efficient emission pathways towards a certain climate target, like the internationally agreed target to keep global temperature increase below 2 °C compared to pre-industrial levels (the 2 °C climate target). However, different timing of reductions lead to different transient temperature increase over the course of the century and subsequently to differences in the time profiles of not only the mitigation costs but also adaptation costs and residual climate change damage. This study adds to the existing literature by focussing on the implication of these differences for the evaluation of a set of three mitigation scenarios (early action, gradual action and delayed action), all three limiting global temperature increase below 2 °C above pre-industrial levels, using different discount rates. The study shows that the gradual mitigation pathway is, for these discount rates, preferred over early or delayed action in terms of total climate costs and net benefits. The relative costs and benefits of the early or delayed mitigation action scenarios, in contrast, do strongly depend on the discount rate applied. For specific discount rates, these pathways might therefore be preferred for other reasons, such as reducing long-term uncertainty in climate costs by early action.

Keywords Adaptation costs · Avoided damage · Climate mitigation · Discount rate · Mitigation costs · Net benefits · Residual damage

1 Introduction

As part of the international climate negotiations around the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen (2009) and Cancún (2010), parties have agreed in the Copenhagen Accord and the Cancún Agreements to collectively reduce greenhouse gas emissions with the aim to limit global mean temperature increase to less than

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2 °C above pre-industrial levels (UNFCCC 2009, 2010), the 2 °C climate target, in order to avoid dangerous anthropogenic climate change. Research has indicated that stringent emission reductions will be required to meet this climate target of 2 °C (Riahi et al. 2013; van Vuuren et al. 2007). While many countries have formulated reduction proposals (pledges) for 2020, assessments of these pledges have concluded that the emission reductions associated with them fall short of those consistent with this 2 °C climate target, based on least-costs emission reduction pathways from 2010 onwards (Hof et al. 2013; UNEP 2013; UNFCCC 2009, 2010). In this context, several studies have started to analyse the feasibility and costs of delayed action scenarios that still have a high probability to remain below 2 °C temperature change (Jakob et al. 2012; Kriegler et al. 2013a, b, 2014; Luderer et al. 2013; Riahi et al. 2013; Rogelj et al. 2013). Most of these studies concluded that achieving the 2 °C target is still technically feasible provided ambitious action is taken in the next decades. However, the studies also indicate that the longer action is delayed, the more expensive change becomes and the greater the risk of not meeting the 2 °C goal (Kriegler et al. 2014; Riahi et al. 2013).

All aforementioned studies have in common that the main focus is on mitigation costs. None of the studies have analysed the implications of different timing of 2 °C emission pathways for adaptation costs and climate change damage. While there is a large body of literature looking at the total costs associated with climate change and climate policy, nearly all these studies focus on meeting different climate targets, instead of on the effect of timing for one climate target (Agrawala et al. 2011; Bosello et al. 2013; de Bruin et al. 2009b; Hof et al. 2009). However, within the group of 2 °C emission pathways, the timing of mitigation will influence temperature and radiative forcing projections as well and therefore also the total costs. In fact, studies do claim that early action would result in lower risks or less damage and adaptation costs (thus benefits) (Warren et al. 2013). Similarly, while delaying mitigation action would lead to lower near-term mitigation costs, it also would lead to higher transient temperature increase and thus adaptation costs and damages. Still, up to now, very little studies have been published that look at the timing aspect on the combined effect of mitigation, adaptation and damage within emission pathways that aim at remaining below 2 °C temperature change. This information is, however, clearly relevant for the ongoing climate negotiations towards the Paris Conference of Parties in 2015.

The objective of this study is to compare the effect of timing in greenhouse gas emission reductions on the mitigation costs, adaptation costs, damage, avoided damage and net benefits. It compares three global emission pathways, called early action, gradual action and delayed action, each with the same climate target (to limit global mean temperature increase to less than 2 °C above pre-industrial levels), but with different timing in greenhouse gas emission reductions, and analyses the effect of different discount rates on the results. For the analysis, the Framework to Assess International Regimes for the differentiation of commitments (FAIR) is used to show the trade-offs in mitigation, adaptation and damage of the three alternative timing profiles. This FAIR model is part of the Integrated Model to Assess the Global Environment (IMAGE) Integrated Assessment Modelling framework (Stehfest et al. 2014).

2 Method of analysis

2.1 Model description and main assumptions

The analysis of the three mitigation scenarios and the baseline has been done using the FAIR policy model (den Elzen et al. 2008, 2013a; Hof et al. 2009) and The IMage Energy Regional model (TIMER) energy model (van Vuuren et al. 2006, 2011), both part of the IMAGE Integrated Assessment Modelling framework (Stehfest et al. 2014).

The FAIR model is used to construct greenhouse gas emission pathways consistent with a predefined long-term climate target. The model determines a least-costs approach of reduction measures across the emission sources of greenhouse gases covered by the UNFCCC Kyoto Protocol. The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) 6 climate model (Meinshausen et al. 2011) is used for calculating radiative forcing levels and temperature increase projections. FAIR calculates mitigation costs based on regional gas- and source-specific marginal abatement cost (MAC) curves, and adaptation costs and residual damage based on the functions of de Bruin et al. (2009a), which are integrated with the FAIR model as described in Hof et al. (2009). The costs calculated in this paper capture the direct costs of emission reduction, adaptation costs and residual damage, but not the macroeconomic implications of these costs. Costs are modelled in 2005 US dollars and presented as share of gross domestic product (GDP).

For energy- and industry-related carbon dioxide (CO_2) emissions, the MAC curves are time and pathway dependent and are determined using the TIMER energy model by imposing a carbon tax and recording the induced reduction in CO_2 emissions. The behaviour of the TIMER model is mainly determined by the substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multinomial logit models that describe investments in new energy production and consumption capacity. The demand for new capacity is limited by the assumption that capital goods are only replaced at the end of their technical lifetime. The long-term prices that drive the model are determined by resource depletion and technological development. Technological development is determined using learning curves or through exogenous assumptions. Emissions from the energy system are calculated by multiplying energy consumption and production flows by emission factors. A carbon tax can be used to induce a dynamic response, such as an increased use of low- or zero-carbon technologies, energy efficiency improvements and end-of-pipe emission reduction technologies. Negative emissions can be achieved by a combination of the use of bioenergy and carbon capture and storage.

For modelling non-CO_2 gases (such as methane, nitrous oxide, sulphur dioxide and ozone-depleting substances), MAC curves from the energy modelling forum’s 21th study (EMF21) project (Weyant et al. 1996) were used. The maximum abatement potential in these curves differs per non-CO_2 emission source. These MAC curves were made consistent with the business-as-usual emission levels used here and made time dependent to account for technology change and the removal of implementation barriers as described by Lucas et al. (2007).

The damage and adaptation cost curves of de Bruin et al. (2009a, b) are based on the total damage projections by Nordhaus and Boyer (2000), but estimates of adaptation costs have been used (including those of Agrawala and Fankhauser 2008) to separate these curves into an adaptation costs function and a residual damage function. The exact functions and calibrations are given in Hof et al. (2009). Adaptation costs are those costs associated with adaptation to the impacts of climate change. Residual damage is damage from climate change that remains after adaptation. In the FAIR model, both adaptation costs and residual damage depend on the global emission pathway and its associated temperature increase projection (climate model) and the cost-optimal level of investment in adaptation measures (Hof et al. 2009). This cost-optimal level is calculated by the model minimising total damage and adaptation costs. Clearly, the mitigation costs, adaptation costs and damage estimates are subject to uncertainty. We will discuss the impact of the uncertainties for our conclusions in uncertainty and discussion section of this paper.

2.2 Scenario assumptions

2.2.1 Baseline scenario

The business-as-usual or baseline projections is an update of the Organisation for Economic Co-operation and Development (OECD) Environmental Outlook (OECD 2012) as calculated by the IMAGE modelling framework (Stehfest et al. 2014). The model framework is calibrated to 2005 and 2010 historical data estimates of population, GDP growth, fossil fuel prices, energy demand and emissions from various databases [UNFCCC, World Bank, International Energy Agency (IEA), Emissions Database for Global Atmospheric Research (EDGAR)]. The 2010 emissions are therefore projections based on modelling and scenario assumptions and may therefore differ from very recent global emission estimates [e.g., EDGAR 4.3 (JRC/PBL 2014)].

The scenario aims to describe a plausible trajectory for emissions given medium population and income projections and assuming that no new policies will be introduced to mitigate climate change. The baseline scenario only includes national domestic energy policies as implemented before 2010. The projections are based on the GDP projections by the OECD ENV-Linkages model (Burniaux and Chateau 2010) developed for the OECD Environmental Outlook (OECD 2012). For population, the scenario assumes the UN medium population growth trajectory (OECD 2012). Finally, for energy the scenario follows a trajectory similar to the IEA's baseline scenario up to 2030 and similar trends thereafter.

The climate impact of the baseline projection in our model is described by radiative forcing, measured in watts per square meter (W/m^2) and defined as the difference in solar insolation absorbed by the earth system and energy radiated back to space. A positive forcing warms the earth system. As a result of the assumptions, in our baseline projection greenhouse gas emissions increase throughout the century and lead to a radiative forcing of 6.1 W/m^2 by 2100, which would likely lead to a temperature increase of around 3.5 °C compared to pre-industrial levels by 2100, rising further thereafter. The baseline scenario is used for comparison with the outcomes resulting from the mitigation scenarios.

2.2.2 Mitigation scenarios

The three mitigation scenarios in this study are defined by the timing of action. All scenarios have an equal (assumed) radiative forcing target of 2.8 W/m^2 in the year 2100 and different starting points of mitigation (Fig. 1 and Table 1). The radiative forcing target of 2.8 W/m^2 is compatible with the climate target of a temperature increase of maximum 2 °C above pre-industrial levels.

The gradual action scenario assumes that for 2020, enhanced ambitious policies at a national level are implemented in order to meet the conditional 2020 pledges made by countries under the Cancún Agreements (UNFCCC 2010). Some countries have submitted both a high pledge that is conditional on a high level of ambition from other countries or domestic legislation and a low pledge that is unconditional (Den Elzen et al. 2010). After 2020, emissions decrease steadily towards approximately zero in 2100. This scenario assumes that each country put forward ambitious national commitments to make a transition right after 2020 towards a global agreement aimed at the 2.8 W/m^2 target.

The delayed action scenario assumes a full implementation of the less ambitious unconditional 2020 pledges and a similar reduction effort towards 2030, which is

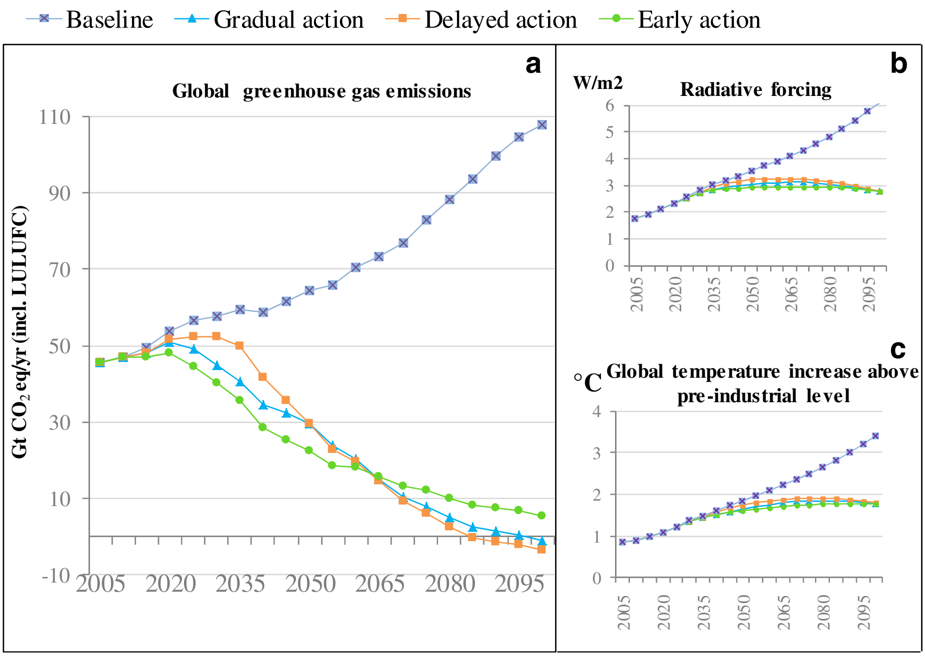

Fig. 1 Climate indicators for the baseline and three mitigation scenarios on global level; greenhouse gas emissions (**a**), radiative forcing (**b**) and temperature (**c**). Note: gigatonne (1 billion metric tonnes) CO_2 equivalent (Gt CO_2eq) emissions refer to the global warming potential-weighted sum of six Kyoto greenhouse gas emission categories, i.e. CO_2, CH_4, N_2O, PFC, HFC and SF_6

compensated by increased action after 2030 in order to still reach the 2.8 W/m^2 target. This scenario assumes that countries put forward national commitments in an agreement. However, emission reductions by 2030 would be less ambitious than those under the gradual action scenario. After 2030, action is ratchet up significantly to make up for the delay in previous decades. This means that the rising emissions until 2030 are followed by a steep decrease afterwards and net negative global emissions after 2080.

The early action scenario assumes immediate mitigation action from 2015 onwards. This leads to more stringent emission reductions in 2020 than implied by the current conditional 2020 pledges. Because of this early action, this scenario requires less stringent climate policies by the end of the century and a global emission level above zero. It presumes a world where nations are driven by ambition and long-term policy visions to facilitate a renewable energy transition—even more so than in the gradual action scenario (Garibaldi 2014; Haites et al. 2013; Hohne et al. 2013).

For the gradual and delayed scenarios, it is assumed after 2020 and 2030 (Table 1) a least-cost emission reduction pathway is implemented by minimising the cumulative discounted mitigation costs over the period 2015–2100 (see 'Model description and main assumptions' section). The early action scenario differs, as its emission path is fixed towards 2040, and assumed to be about 10 % below the gradual scenario. From 2040 onwards, this scenario also assumes a least-cost emission reduction pathway.

Table 1 Scenario description and model assumptions for the three mitigation scenarios (early action, gradual action and delayed action) and the baseline projection as analysed in this study, using the IMAGE Integrated Assessment Modelling framework

Scenario assumptions

Scenario	Radiative forcing target (2100)	Timing joint of action	Description
Baseline	6.1 W/m^2	–	Baseline scenario based on the OECD Environmental Outlook 2012.
Early action	2.8 W/m^2	2015	This scenario focuses on immediate action, allowing for less stringent climate policy in the second half of the century. Between 2011 and 2040, ambitious actions are assumed, which lead to emissions which are 10 % below the gradual action path. After 2040, full participation is assumed aimed at achieving the 2.8 W/m^2 target with lowest cumulative discounted mitigation costs
Gradual action	2.8 W/m^2	2020	Between 2011 and 2020, the conditional pledges are implemented. After 2020, full participation of all countries in the emission reductions is assumed, which are distributed optimally over time, such that cumulative discounted mitigation costs over the 2020 to 2100 period of achieving the 2.8 W/m^2 target are minimised
Delayed action	2.8 W/m^2	2030	Between 2011 and 2020, the unconditional pledges are implemented. This trend is extrapolated towards 2030. After 2030, full participation of all countries is assumed with least-costs emission reduction pathway aimed at achieving the 2.8 W/m^2 target. Strong reduction policy after 2030 are needed to compensate for the extra emissions

For each pathway, the radiative forcing target (climate target) is given, the timing of mitigation action and the general description of the scenario

2.3 Caveats

In all three mitigation scenarios, it is assumed that there are no restrictions in mitigation technologies. In this study, the three scenarios are feasible assuming a full availability of mitigation technologies. In particular, the delayed action scenario relies increasingly on the availability of specific mitigation technologies, in particular of large-scale deployment of bioenergy and carbon capture and storage. This is also found in other model studies (Kriegler et al. 2013b, 2014; Riahi et al. 2013). Limitation in the technological availability in combination with the delay in action has the risk that the ambitious climate target becomes infeasible.

Furthermore, the 2010 emission level in this current study is within the Intergovernmental Panel on Climate Change (IPCC) range (IPCC 2014). However, it is in the lower range, as this study takes into account relatively low emissions from land use/land cover change. Higher land use emissions might affect the feasibility and mitigation costs projections of the scenarios as presented in this study, as explored in Kriegler et al. (2014).

3 Results

3.1 Global mitigation costs, adaptation costs and residual damage

The model analysis shows that for the three mitigation scenarios, annual mitigation costs of achieving the 2.8 W/m^2 target are projected to be around 1–2 % of global GDP (Fig. 2). The results show a relatively sharp peak in annual cost for the early action scenario (around 2030–2040) and delayed action scenario (around the middle of the century). In the gradual action scenario, mitigation costs steadily increase and has the most equally distributed trajectory (with no strong peaks in costs) compared to the other scenarios.

The annual damage and adaptation costs stabilise at the end of the century respectively at around 1.3 and 0.2 % of global GDP for each mitigation scenario given the stabilisation of the temperature in these scenarios. In the baseline, however, these costs would increase towards 2.5 and 1.2 % of global GDP and keep increasing afterwards as temperature keeps rising. Between 2040 and 2100, adaptation costs and residual damage differ somewhat between the mitigation scenarios as a result of their different temperature increase projections (Fig. 2).

The results in terms of damage projections are comparable to those presented in other studies as for instance the Stern report (Stern 2006). Stern estimates an 11.3 % loss in global GDP by 2200 based on a temperature increase by 2200 of 7.5 °C, whereas our projection is about 8 % loss of GDP in 2200 based on a temperature increase of 5.5 °C (Hof et al. 2009). If we would assume a 7.5 °C temperature increase by 2200, our damage loss projection would be about 14 % in 2200, so a fourth higher compared to Stern.

Figure 3 shows the cumulative discounted climate costs (present value) between 2015 and 2100, divided into mitigation costs, adaptation costs, residual damage and extra damage if no adaptation measures are taken, for the different mitigation scenarios. A constant discount rate of 5 and 2 % were used in this study. In integrated assessment models, discount rates of 5 % are commonly used (IPCC 2014; Riahi et al. 2013). The lower discount rate of 2 % is included as several scholars argue that for long-term problems with large risks of irreversible events, a lower discount than usually applied in cost-benefit analyses should be used (Stern 2006; Weitzman 1994).

It is interesting to note the differences in costs between the scenarios and how these differences depend on the discount rate. The present value of mitigation costs in the gradual and delayed mitigation action scenarios are much lower (27 %) than in the early action scenario with a discount rate of 5 %. However, with a discount rate of 2 %, future costs are relatively more important, resulting in a much smaller difference in the present value of

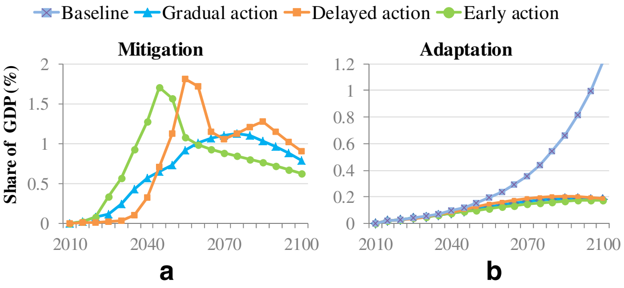

Fig. 2 Global annual mitigation costs (**a**), adaptation costs (**b**) and residual damage (**c**) in different years for the three mitigation scenarios

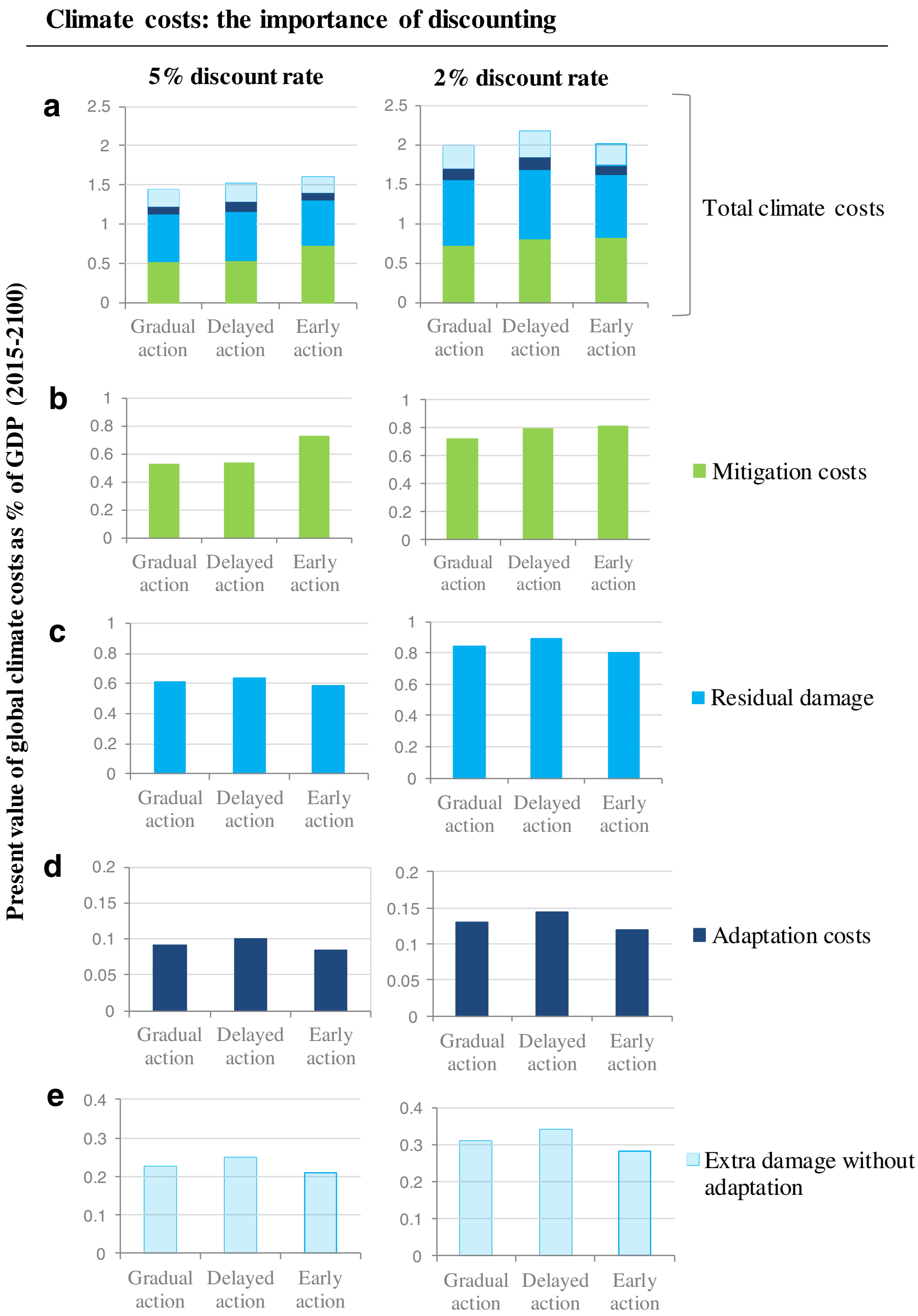

Fig. 3 Global cumulative discounted mitigation cost (**b**), adaptation costs (**c**), residual damages (**d**) and extra costs without adaptation (**e**) over the period 2015–2100 for the three mitigation scenarios

mitigation costs between the scenarios—although the early action scenario still has the highest and the gradual scenario the lowest present value of mitigation costs. The scenarios thus show large relative differences in mitigation costs for different discount rates as these differ especially in the short term.

In contrast, as timing of mitigation impacts the level of damage and adaptation costs in the long term only, the discount rate itself has little impact on the relative differences in the present value of adaptation costs and damage between the scenarios. Still, some substantial differences exist between the scenarios. In the delayed scenario, the present value of adaptation costs is 19 % higher than in the early action scenario and 10 % higher than in the gradual action scenario. The present value of residual damage in the delayed scenario (in a situation with adaptation) is 10 % higher than the early action scenario and 5 % higher than the gradual action scenario. In a situation without adaptation, residual damage is even 18 and 10 % higher, respectively, for early action and gradual action.

Furthermore, the damage and adaptation cost projections do alter the comparison between mitigation scenarios. For example, early action projects the lowest costs for damage and adaptation for both discount rates and is therefore often referred to as a preferred scenario (Arrow et al. 2013; Garibaldi 2014; Warren et al. 2013). However, the higher mitigation costs more than offsets the lower damage and adaptation costs with a discount rate of 5 %, leading to the early action scenario being the one with the highest overall costs. With a 2 % discount rate, future costs are weighted more heavily, resulting in the delayed action scenario being the one with highest overall costs. In this study, gradual action has the lowest projected overall costs for both discount rates.

Figure 3 also emphasises the importance of adaptation for each type of mitigation scenario, as shown by the extra damage without adaptation. This is damage that will occur without adaptation to climate change. Figure 3 shows that adaptation thus has an important contribution in reducing damage. In this study, adaptation reduces the present value of overall climate costs by around 10 %.

3.2 The effect of timing on global mitigation costs and benefits

As described in the previous section, reducing greenhouse gas emissions to limit temperature increase to 2 °C requires significant mitigation costs. This section compares the mitigation costs of the three mitigation pathways with the benefits (avoided damage) relative to the baseline. Avoided damage is defined as the difference in the sum of adaptation costs and residual damage between the baseline and the mitigation scenario. Net benefits refer to the total avoided damages of the mitigation scenario compared to the baseline, minus the mitigation costs of the mitigation scenario. Net benefits thus represent the difference in the total climate costs (the sum of mitigation costs, adaptation costs and damage) in the mitigation scenarios and the baseline.

This comparison provides insight into the differences between the mitigation pathways, and it cannot be used to compare the costs and benefits of the mitigation pathways with those of the baseline. For such a comparison, a much longer time horizon than applied in our model would be needed.

Figure 4 compares the undiscounted annual mitigation costs as share of global GDP with the avoided damage for each of the three mitigation scenarios, all relative to the baseline (see next section for an uncertainty analysis). In calculating these avoided damage for the mitigation scenarios, this study assumes no adaptation effort in the baseline. Global avoided damage increases towards almost 2.5 % of GDP per year at the end of the century and is expected to increase further thereafter. Mitigation costs are projected to exceed the avoided damage in the short to medium term, but in the long term, avoided damage outweighs mitigation costs. When this break-even point will occur differs between the scenarios and their timing of mitigation. In

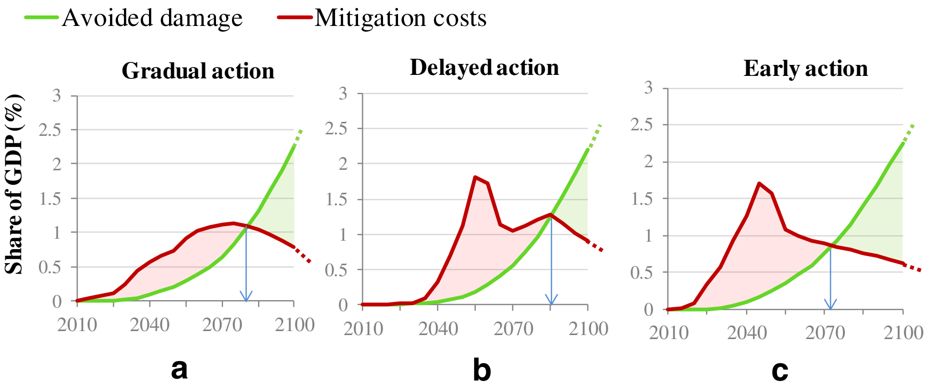

Fig. 4 Global annual mitigation costs and avoided damage in the three mitigation scenarios (with adaptation) relative to the baseline (with no adaptation)

the early action scenario, avoided damage exceeds mitigation costs from around 2075 onwards, in the gradual action scenario this occurs around 2080, while in the delayed action scenario this occurs only around 2085–2090.

Earlier mitigation therefore results in earlier net benefits—but also in higher net costs in the short term. To analyse the cumulative effect of these costs and benefits between 2015 and 2100, Fig. 5 depicts the net present value of the benefits (i.e. cumulative discounted benefits minus cumulative discounted costs) as share of global GDP and relative to the gradual mitigation scenario. All mitigation scenarios (including adaptation) lead to net benefits compared to the baseline scenario with no adaptation. The lower panel of Fig. 5 compares the relative net benefits of the early action and delayed action scenario compared to the gradual mitigation scenario. It shows that for both discount rates, gradual action leads to the largest net present value. The preference for early action or delayed action is strongly dependent on the discount rate used to calculate the net present value of the benefits. With a 5 % discount rate, gradual action and delayed action have substantial larger net present value of the benefits than early action, whereas with a 2 % discount rate, the net present value of the benefits is very similar across all three mitigation scenarios.

4 Uncertainty and discussion

4.1 Uncertainty in costs and benefit estimates

There are many uncertainties that influence the mitigation costs and avoided damages. Mitigation costs, for instance, depend on the expected technology development, fossil fuel price development, potential for mitigation and the rate measures that can be implemented. Different models provide different insights into the level of these costs. Adaptation costs and residual damage depend on the level of climate change, uncertainties in damage functions and the effectiveness of adaption. Figure 6 illustrates the role of some of these uncertainties. For mitigation costs, the uncertainty range shown is the time-dependent 25th to 75th percentile ranges of the mitigation costs projections of the IPCC fifth assessment report (IPCC 2014), covering the impacts of baseline differences and model differences in various studies. The absolute ranges over time as provided in the AR5 are applied to the gradual scenario, as this

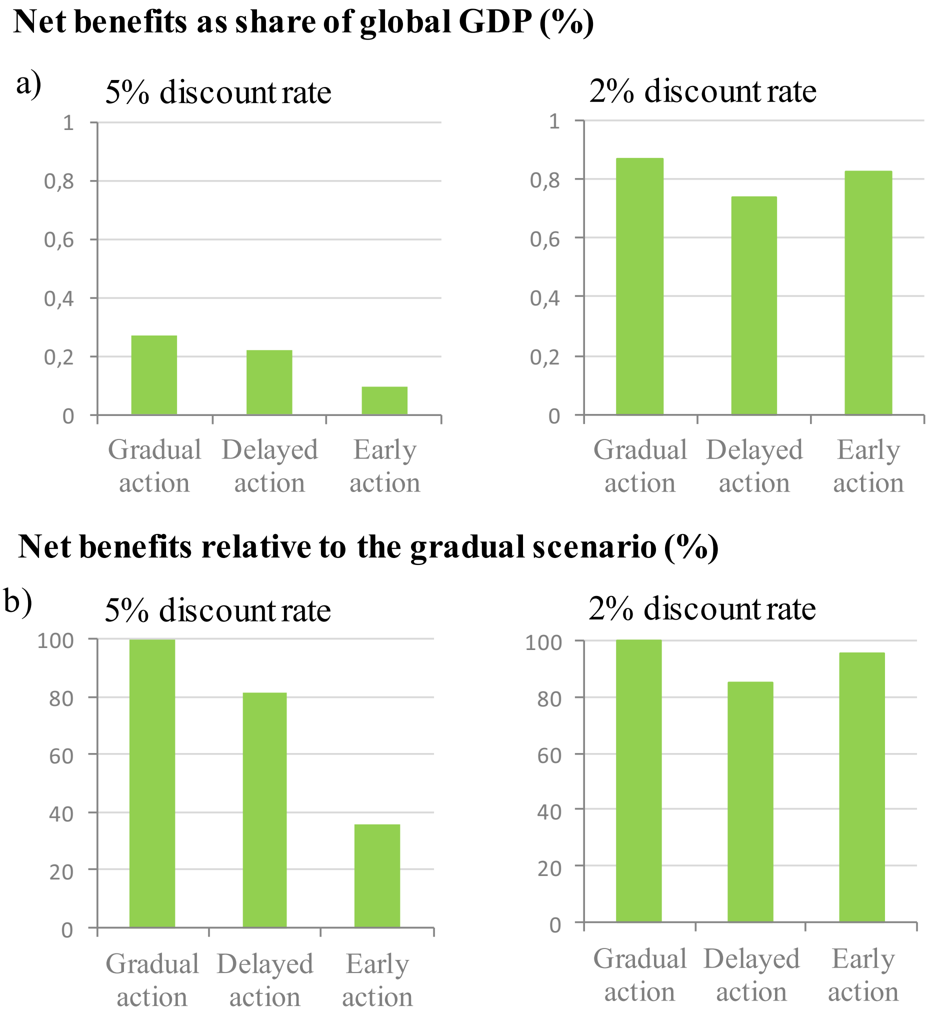

Fig. 5 Global cumulative discounted net benefits of mitigation and adaptation over the period 2015–2100, relative to the baseline (with no mitigation and adaptation) for a 5 and 2 % discount rate. Results are presented as share of global GDP (**a**) and as an index compared to the gradual action scenario (**b**)

scenario is most similar to those presented by the IPCC. For the other two mitigation scenarios, the same relative uncertainty level has been assumed.

Uncertainty in damage is large because of the difficulty to estimate the future market and especially the non-market impacts of climate change. The default damage projection used in this study, derived from the Regional Integrated Climate-Economy model (RICE) model, is similar to the mean projection as used in the Stern review (Stern 2006), which are based on the Policy Analysis of the Greenhouse Effect (PAGE) 2002 model (Hope 2006). Therefore, we can use the uncertainty range as provided by Stern to give an indication of the uncertainty range in damage projections. Based on Table 6.1 of the Stern review, we use an uncertainty range of +150 and −80 % relative to the default projection. Admittedly, this uncertainty range

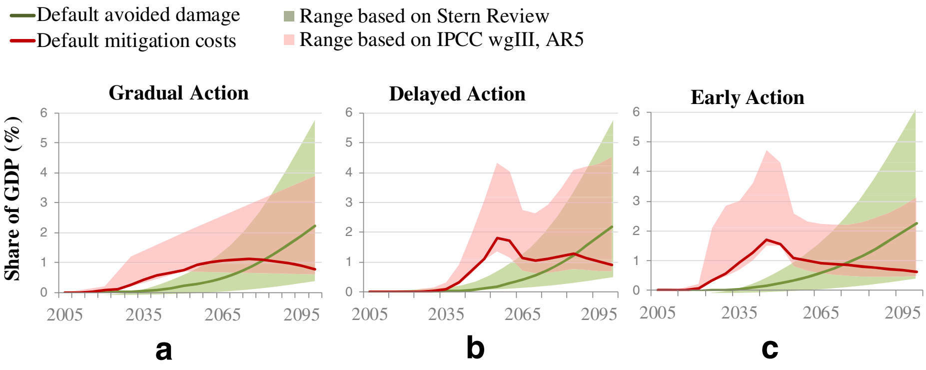

Fig. 6 Uncertainty in global annual mitigation costs and avoided damage in the three mitigation scenarios (source uncertainty ranges—Stern 2006; IPCC 2014)

is only indicative as the real uncertainty range is still largely unknown and dependent on the—unknown—probability of irreversible large-scale events.

As shown in Fig. 6, the uncertainty ranges are very large. Interestingly, the early action scenario now actually benefits from reducing the uncertainty at the end of the century. As a result, this scenario has the highest probability of avoided damage exceeding mitigation costs by the end of the century. At the same time, however, the figure also shows that in this scenario mitigation costs can be much higher than avoided damages early in the century (having a large impact on the net present value of the benefits).

A key finding of the study is that for considerations related to timing, mitigation costs dominate the overall assessment (partly as a result of the timing). Studies have shown that the mitigation costs estimates of the FAIR/TIMER framework as applied here are within the range of the literature, but on average on the low side. This implies that the results would in most cases be robust against using alternative mitigation costs estimates.

4.2 Other factors affecting the outcomes of the study

While this study has quantified the direct mitigation costs, adaptation costs and residual damages, the projections do not include co-benefits or negative externalities. Examples of negative externalities are allocation issues of biofuel production, as it competes with food production, or landscape deterioration due to wind power. Examples of positive externalities, or co-benefits, are improved air quality due to less combustion of fossil fuels, improved energy security or better energy infrastructure. Little information is available on the valuation of these externalities.

A second limitation is that this study only looked at the costs and benefits of mitigation pathways, using uncertain parameters as mitigation costs, adaptation costs and damage. Arguably, other factors such as political and technical feasibility, social acceptance and risks are equally important. Decision-makers are often more interested in information on avoided risks expressed in physical terms than in aggregated monetary measures for average situations. Delaying action could also lead to the need of very rapid implementation rates (Kriegler et al. 2014; Riahi et al. 2013), which might be infeasible. On the other hand, early action could lead to risk of much higher costs if societies turn out to be less able to swiftly implement climate policies. Feasibility of all 2 °C scenarios will thus depend on the translation of it in the next climate agreement and implementation by countries afterwards.

5 Conclusions

In this study, the IMAGE Integrated Assessment Model has been used to explore different timing strategies of mitigation towards a 2 °C climate target in 2100 (i.e. to keep global temperature increase below 2 °C compared to pre-industrial levels). In the calculations, a 5 and 2 % discount rate was used and three mitigation strategies: early action, gradual action and delayed action. This analysis provides insight in the effect of timing of emission reductions towards a similar climate target on not only mitigation costs but also on adaptation costs, damage, avoided damage and net benefits. The following main conclusions can be drawn, which should be interpreted with care given the large uncertainties inherent in the climate system.

Mitigation costs strongly depend on timing of mitigation. With early action and delayed action, annual mitigation costs peak at almost 2 % of global GDP (range 1.5–5 %), while in the gradual action scenario, mitigation costs are equally distributed trajectory over the years and reach a maximum of about 1.2 % of global GDP (range 0.5–4 %). The annual mitigation costs of achieving a 2.8 W/m^2 target are projected to peak 10 to 40 years earlier in our early action scenario than our delayed action scenario. Due to the different time paths of mitigation, the present value of mitigation costs between 2015 and 2100 is substantially impacted by the choice of discount rate.

This study finds that the timing of mitigation clearly impacts the level of damage and adaptation costs over the century, as timing influences the temperature increase projection of the scenarios. Global damage and adaptation costs mainly occur in the second half of the century. Between 2040 and 2100, adaptation costs and residual damage differ between the mitigation scenarios as a result of their different transient temperature increase projections. These annual costs amount to about 1 % (range 0.2–1.5 %) of global GDP in the mitigation scenarios and 3.5 % (range 0.5–5.5 %) in the baseline. Because these effects become mainly visible in the long term, the present value of damage and adaptation costs between 2015 and 2100 (and thus avoided damages or benefits) is less sensitive to the level of discount rate. Overall, the present value of damage and adaptation costs (for both a 2 and 5 % discount rate) of the early action case is 10 % lower compared to a delayed action path. With gradual action, this present value is 5 % lower than the delayed action path.

Taking into account all climate costs (mitigation, adaptation and damage) and net benefits (avoided damage minus mitigation costs), gradual action has the lowest present value of total costs and highest net present value of benefits for both the 2 % discount and 5 % discount rate. The preference for early action or delayed action in mitigation, however, is strongly dependent on the discount rate chosen. As mitigation costs are a key factor in total costs, the gradual pathway is found to lead to lowest total cumulative discounted climate costs and highest cumulative discounted net benefits for the two discount rates looked at over the period 2015 to 2100. However, in the case of early action and delayed action, adding damage and adaptation costs to mitigation costs and considering different discount rates in evaluating the timing of mitigation pathways do impact the evaluation of these two different pathways. For instance, early action is relatively attractive with a 2 % discount rate and delayed action with a 5 % discount rate. With a 2 % discount rate, early action is preferred over delayed action, due to its lower cumulative damage and adaptation costs, resulting in higher net benefits. However, with a 5 % discount rate, these lower damage and adaptation costs are outweighed by the higher mitigation costs of early action in the first half of the century compared to delayed action, resulting in higher net benefits for the latter scenario.

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Compliance with ethical standards

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Conflict of interest The authors of this paper declare that they have no conflict of interest and that this paper complies with the ethical rules applicable for this journal.

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