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Modeling adaptation as a flow and stock decision with mitigation

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Abstract An effective policy response to climate change will include, among other things, investments in lowering greenhouse gas emissions (mitigation), as well as short-term temporary (flow) and long-lived capital-intensive (stock) adaptation to climate change. A critical near-term question is how investments in reducing climate damages should be allocated across these elements of a climate policy portfolio, especially in the face of uncertainty in both future climate damages and also the effectiveness of yet-untested adaptation efforts. We build on recent efforts in DICE-based integrated assessment modeling approaches that include two types of adaptation—short-lived flow spending and long-lived depreciable adaptation stock investments—along with mitigation, and we identify and explore the uncertainties that impact the relative proportions of policies within a response portfolio. We demonstrate that the relative ratio of flow adaptation, stock adaptation, and mitigation depend critically on interactions among: 1) the relative effectiveness in the baseline of stock versus flow adaptation, 2) the degree of substitutability between stock and flow adaptation types, and 3) whether there exist physical limits on the amount of damages that can be reduced by flow-type adaptation investments. The results indicate where more empirical research on adaptation could focus to best inform near-term policy decisions, and provide a first step towards considering near-term policies that are flexible in the face of uncertainty.

1 Introduction

Mitigation and adaptation are two of the primary responses available to policymakers to reduce the risks of climate change.[1] Mitigation is a reduction in the rise of atmospheric greenhouse gas (GHG) concentrations occurring via emissions abatement or carbon sequestration, while adaptation can be defined as the set of actions taken to respond to a changing climate that

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[1] Other possible responses include R&D and geoengineering, which are not treated here.

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improve welfare, do not change the climate as the goal, and would not have been taken were the climate not changing (Felgenhauer and Webster 2013). The global climate policy with the lowest total societal losses will be a portfolio of these two responses, simultaneously implemented and with tradeoffs and interactions between them. As the effects of climate change are likely to begin to be felt over the next several decades and as the political challenges to coordinated mitigation remain, increasing attention is turning to the appropriate allocation of efforts between mitigation and adaptation. Further, adaptation consists of many different possible investments with widely varying dynamic profiles. In the face of significant uncertainty in the severity of future climate damages and the effectiveness of yet untested adaptation responses, a critical question is how relative effort should be allocated across all these possible investments.

Climate-economy policy optimization models that incorporate both mitigation and adaptation as explicit decision variables have been developed that solve for the optimal trajectories of mitigation and adaptation over time. Notable among dynamic analyses are those models that are based on the DICE (Nordhaus 2007) or the regionalized RICE (Nordhaus and Yang 1996) integrated assessment models (IAMs).[2] In these models, adaptation is a single aggregated activity, representing all possible adaptation types, that reduces the costs of climate change damages and is implemented proportionally to the level of its net benefits relative to other policy options. Compared to the case where mitigation is the only available response, welfare is improved by including the option to adapt.

Mitigation and adaptation are distinctly different in their timescales of policy effectiveness and the mechanism of how each approach reduces damages dynamically over time and under uncertainty. Spending on both strategies will repeat over time, but that for adaptation allows for flexibility on the desired longevity of the investment's effects as well as the technology that can be paired with different types of damages and damage profiles. Thus, unlike mitigation, adaptation allows for targeted responses to specific damages for as long as it is cost effective. It follows that using a single policy variable within an IAM to represent adaptation measures with varying lifetimes and constraints may not accurately portray the tradeoffs between mitigation and adaptation, particularly under uncertainty (Felgenhauer and Webster 2013). As one step towards representing this heterogeneity, adaptation can be disaggregated into two sub-types, flow and stock adaptation, which represent two points along a range of adaptation lifetimes.

Flow adaptation is a comparatively low-cost response to climate change that provides short-term benefits in the form of damage reductions, but which must be repeated over time due to its limited adaptive coping range. It is flexible because it can be ramped up or down relatively quickly within the limits of the applied technology. But it is only sustainable as long as the particular *technology* and *amount of application* can effectively reduce damages. Examples of flow adaptation include beach renourishment to protect eroding coastlines with periodically resupplied imported sand, or in the health sector, the wider distribution of medicines to treat climate-related diseases or cheap prophylactic measures such as the use of mosquito nets. Higher frequency heat waves could be alleviated through the subsidization of air conditioners for vulnerable segments of the population. Another example is "doing more" in the agricultural sector, such as irrigating more (if the water is available given current infrastructure), adding more fertilizer, or using more pesticide. It could also mean more sophisticated, ongoing, and evolving behavioral changes such as experimenting with integrated pest management, altering crop planting dates, or changing the type of crops grown. Damages from extreme events such as floods can be lowered somewhat with case-by-case emergency responses that need to be repeated after every disaster.

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[2] Others are listed in the Online Resources.

Adaptation stock is comprised of relatively large-scale, expensive, and long-lived investments, with a high adaptive capacity that declines slowly over time due to capital depreciation and rising climate damages. It is comparatively irreversible and "committed," with high sunk costs compared to any salvage value. Adaptation stock responses are limited by both the rigidity of the applied technological approach, which cannot be changed significantly once built or implemented, as well as its relatively long lifespan of several decades (matching the length of time that it takes for the effect of present-day mitigation investments to be felt), with a high opportunity cost. This stock is often exemplified by "hard" infrastructure investments such as barricades or seawalls to hold off rising seas and protect coastal assets. It also involves the construction of long-lived buildings designed to be resilient to more frequent flooding. For farmers, new stock could include capital investments in harvesting equipment retrofits to allow for the harvesting of different crops under new conditions. The water sector has perhaps the most costly and longest-lived of climate-exposed capital, whether for irrigation, drinking water, sewerage, or drainage, as provided by systems of reservoirs, pipes, levees, and dams. Stock adaptation can also be of the "soft" variety, such as long-term investments in the development of new vaccines for climate-related diseases, capacity building to improve models and other forecasting tools, or policies to promote behavioral change and other types of facilitative adaptation.[3]

This research adds to the emerging modeling literature that includes mitigation and two types of adaptation activities—short-lived, flexible, and relatively cheap flow spending with a lower adaptive capacity, and long-lived and depreciable adaptation stock investments with a higher adaptive capacity (e.g., Lecocq and Shalizi 2008; Bosello et al. 2009, 2010; Yohe et al. 2011).[4] In this paper we present results from a DICE-based modeling of the climate and economy that builds directly upon AD-DICE (de Bruin et al. 2009), and follows the framework of subsequent versions that distinguish between stock and flow adaptation and use a constant elasticity of substitution function for aggregating the two adaptation types (Agrawala et al. 2010, 2011; de Bruin 2011). Agrawala et al. (2010, 2011) develop a new version of AD-DICE with mitigation and stock and flow adaptation and compare its results to the AD-WITCH model, which in turn includes mitigation, stock and flow adaptation, and a fourth category called adaptation capacity. De Bruin (2011) extends the analysis of differentiated stock and flow adaptation for varying discount rates, climate damage levels, and adaptation stock depreciation rates. A general finding from these sensitivity analyses is that if gross (before any adaptation) climate damages are greater, then the aggregate investment in the portfolio of adaptation and mitigation will be greater, although the relative proportions do not change appreciably. Both author groups present results of their detailed global analysis of the climate damages by sector, and the resulting stock and flow aspects of adaptation, drawing on Nordhaus and Boyer (2000) and the AD-RICE model to obtain input factor shares for stock and flow adaptation.

In this paper we focus on exploring the uncertainties that have the greatest impact on the relative proportions within the climate response portfolio of mitigation, short-term flow adaptation, and long-term stock adaptation. We apply a model similar to Agrawala et al. (2010, 2011) and De Bruin (2011) to demonstrate that the relative ratio of flow adaptation,

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[3] This point was noted by an anonymous reviewer. Soft stock in the sense used here incorporates the adaptation capacity of Bosello et al. (2009).

[4] Hall et al. (2012) distinguish between an upfront investment and an incremental strategy with periodic upgrades. Others have modeled mitigation with adaptation characterized as a flow only (Ingham et al. 2007; de Bruin et al. 2009; Felgenhauer and de Bruin 2009; de Bruin and Dellink 2011), or as a stock (Bosello 2008; Dumas and Ha-Duong 2008). Different modeling approaches are described further in the Online Resources. The PAGE model has also been used to analyze both policies simultaneously (e.g., Hope et al. 1993; Hope 2006).

stock adaptation, and mitigation depends critically on interactions among: 1) the relative effectiveness in the baseline of stock versus flow adaptation, 2) the degree of substitutability between stock and flow adaptation types, and 3) whether there exist physical limits on the amount of damages that can be reduced by flow-type adaptation investments. The results from our analysis suggest directions for empirical research on adaptation that would inform near-term allocation of effort between mitigation and adaptation. The analysis here is a first step towards considering near-term policies that are flexible in the face of uncertainty.

In Section 2, we describe the present modeling effort, its calibration, and how it compares and contrasts with previous modeling of adaptation as both a flow and a stock. While we calibrate to Agrawala et al. (2010, 2011) and de Bruin (2011), our modeling framework uses a different adaptation services production function for adaptation stock. This independent modeling means that several parameter assumptions differ across the models while qualitatively the results are similar, as described below. Reference case results for a portfolio of mitigation and flow and stock adaptation are presented in Section 3. In Section 4, we present the impacts on the policy portfolio of simultaneously considering three critical uncertainties: the effect of a capacity limit on flow adaptation, different degrees of substitutability between the two adaptation types, and the relative effectiveness of flow and stock adaptation. The Online Resources presents additional results for varying climate sensitivities and the discount rate. Section 5 has a concluding discussion.

2 Modeling mitigation and multiple adaptation types in a dynamic response portfolio

The Dynamic Integrated Climate Economy (DICE) model, developed originally by Nordhaus (1994), is a simple, forward-looking integrated assessment model of the world climate and economy. The objective is to maximize aggregate utility (social welfare), calculated as the discounted natural logarithm of consumption,[5]

$$U[C(t), L(t)] = L(t)\{\log[C(t)]\}. \tag{1}$$

The control variables are mitigation and investment in capital stock. In each time period, consumption is determined endogenously, subject to available income that is reduced by the costs of climate change (residual damages and mitigation costs). Mitigation is on a [0–1] scale, representing the fractional reduction of greenhouse gas emissions relative to the baseline for that period. Because baseline emissions are always rising, increasing mitigation will not necessarily result in decreasing emissions over time. Mitigation's costs decline over time but its benefits lag far into the future due to the long time scales of the carbon cycle (Nordhaus and Boyer 2000). The formal statement of the problem is

$$\begin{aligned} \max_{I(t),\mu(t)} W &= \sum_t U[C(t), L(t)]R(t) \\ \text{subject to} \quad S(t) &= G\{S(t-1), P(t-1)\} \end{aligned} \tag{2}$$

where t is the time period index, $U(\cdot)$ is the utility function from Eq. (1), $C(t)$ is consumption, $L(t)$ is population, and $R(t)$ is the discount factor. The model is constrained such that $S(t)$ is the vector of states (capital stocks), $G(\cdot)$ is the state transition function, and $P(t)$ is the vector of policy controls (emissions control rate $\mu(t)$ and investment in physical capital stocks $I(t)$). The constraint equations are defined in Nordhaus and Boyer (2000), and for convenience are also

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[5] More recent versions of DICE use an iso-elastic utility function (Nordhaus 2008), which we present in the Online Resources.

given in the Online Resources. Below we only explicitly list the additional or modified variables and equations that represent flow and stock adaptation.

The adaptation portfolio is chosen optimally to maximize the net present value (NPV) of social welfare, and its benefits are felt immediately. Income $Y(t)$ is the total economic output $Q(t)$, reduced by net damages $ND(t)$, adaptation flow costs $AFC(t)$, and mitigation costs $MC(t)$,

$$Y(t) = Q(t)\frac{1-MC(t)-AFC(t)}{1+ND(t)} \tag{3}$$

The service that adaptation provides—reducing damages—can also come from a supply of adaptation stock $H(t)$ that is replenished every period by the policymaker's chosen amount of adaptation stock investments $ASI(t)$. As in Agrawala et al. (2010, 2011) and de Bruin (2011), we incorporate this additional adaptation stock approach. Adaptation stock depreciates at the rate δ_s such that

$$H(t+1) = \left[(1-\delta_s)^{10}\right]H(t) + 10ASI(t). \tag{4}$$

The replenishment and depreciation behavior of adaptation stock is the same as for physical capital stock in this version of DICE, for adaptation stock in other studies (*ibid*., Bosello 2008), and for knowledge stock in economic models of R&D, e.g., Popp (2004). Capital stock $K(t)$ evolves as a function of investment and the depreciation rate of capital, δ_K

$$K(t+1) = \left[(1-\delta_K)^{10}\right]K(t) + 10I(t). \tag{5}$$

Gross damages from climate change $GD(t)$ rise exponentially with temperature

$$GD(t) = \alpha_1 T(t) + \alpha_2 T(t)^{\alpha_3} \tag{6}$$

In each time period, the mitigation of emissions reduces gross damages from the level that would occur under a no-policy business as usual (BAU) scenario. The stock and flow adaptation types combine to form an aggregate level of adaptation services $AD(t)$, reducing these "post-mitigation" gross damages to a further lower level of net damages $ND(t)$ such that

$$ND(t) = GD(t)(1-AD(t)). \tag{7}$$

As in Agrawala et al. (2010, 2011) and de Bruin (2011), flow and stock adaptation responses are combined through a constant elasticity of substitution (CES) production function to provide the aggregate level of adaptation services,

$$AD(t) = \left[\beta AF(t)^{\rho} + (1-\beta)AS(t)^{\rho}\right]^{\frac{\alpha}{\rho}}, \tag{8}$$

where $AF(t)$ is the amount of adaptation flow, $AS(t)$ is the amount of adaptation services derived from adaptation stock, ρ is the substitution parameter between the two adaptation inputs (the elasticity of substitution is $\sigma=1/(1+\rho)$), and α is the returns to scale for adaptation. A CES production function maps out an efficient frontier of inputs for a desired output, which here is the reduction of damages through adaptation services. Alternative forms of adaptation production functions are discussed in the Online Resources. The relative share of flow adaptation as an input factor in the amount of total adaptation is β, and $(1-\beta)$ is the share of stock adaptation in the production of adaptation. Different values for these shares conceptually represent different assumptions about the relative effectiveness of each adaptation type in the base year. We demonstrate the critical impact of this parameter on the optimal mix of climate responses below.

One key difference with previous approaches is that we model adaptation stock with a production function for the adaptation services that it provides, rather than equating the stock level with the reduced damages. Adaptation stock $H(t)$ provides adaptation services $AS(t)$ through the adaptation stock production function,

$$AS(t) = \theta_1 + \theta_2 ln\left(\frac{H(t)}{K(t)}\right), \tag{9}$$

where $K(t)$ is the total amount of non-adaptive capital stock in the economy, and θ_1 and θ_2 are parameters used for calibration. The adaptation stock production function embodies two assumptions. First, adaptation stock lowers damages but with diminishing marginal productivity, as is consistent with other economic models of knowledge or human capital stock. Second, the productivity of adaptation derived from stock is related to the ratio of adaptation stock to the amount of non-adaptive capital in the economy. In the model, adaptation stock is distinct from physical capital that produces economic output—it only reduces damages, and any other positive economic benefits or non-climate change co-benefits it may generate are not included. Adaptation stock productivity rises at a diminishing rate with its level, while higher levels of other capital in the economy shift this productivity downwards.

In DICE, adaptation is equated with all alternative actions that make economic sense when compared to mitigation (Nordhaus 2008). Thus the level of adaptation depends on a rational policymaker's assessment of the best alternative use of productive capital that is otherwise being allocated to mitigation. In this way, adaptation is implicitly included as part of the damage function, where it has already taken place in an assumed optimal way (Cline 2006). Such free market business-as-usual adaptation occurs as actors respond to prices, where the remaining damages are those to which people choose not to adapt because of the prevailing market rate of return (Nordhaus 2008). DICE thus captures autonomous adaptation but not policy-driven adaptation that could drive down total costs further. De Bruin et al. (2009) were the first to change this by incorporating adaptation explicitly into DICE with the AD-DICE model. In AD-DICE, adaptation is a policy variable on a [0–1] scale, with zero representing no adaptation and one being the hypothetical extreme upper bound representing the elimination of all climate damages in that time period. Called "protection" in the first version of AD-DICE (*ibid.*), this flow adaptation $AF(t)$ reduces damages in the current time period t but has no lasting effects. As in AD-DICE, adaptation flow costs $AFC(t)$ increase as a function of the level of adaptation provided:

$$AFC(t) = \gamma_1 AF(t)^{\gamma_2}. \tag{10}$$

As with investments in normal productive capital $I(t)$, investments in adaptation stock reduce the available consumption $C(t)$:

$$C(t) = Y(t) - I(t) - ASI(t). \tag{11}$$

Total adaptation costs are the sum of spending on adaptation flow efforts and investments in adaptation stock, and the net benefits of each adaptation strategy are the portion of damages that are avoided from that type of adaptation minus its cost.

Apart from Eq. (9), our model is the same as that in Agrawala et al. (2010, 2011) and de Bruin (2011). We implement the model in GAMS and solve it as a nonlinear programming problem using the CONOPT solver. In the next section, we describe the calibration of our model parameters to the main results of these previous studies, and show results from a reference case.

3 Calibration and reference case results

The parameters of the stock and flow model are calibrated in three steps to reproduce the key results—the relative investment of mitigation, flow adaptation, and stock adaptation—from Agrawala et al. (2011). First, the three coefficients of the gross damage function (6) were calibrated to minimize the sum of squared differences between gross damages in a no policy run between this model and that of de Bruin (2011). Second, reference case values for parameters are chosen such that the aggregate adaptation production function (8) includes relatively equal shares of flow and stock adaptation as input factors ($\beta=0.49$), an elasticity of substitution between the two adaptation types of $\sigma=2$, and diminishing returns to scale for total adaptation of $\alpha=0.8$. These and other reference case values are listed in Table 1 of the Online Resources. Total adaptation is also constrained below a hypothetical 100 % adaptation level (i.e., negative net damages are not allowed). Third, the two calibration parameters in the adaptation stock production function (9) were chosen to minimize the sum of squared errors of the ratio over time of adaptation stock investment to adaptation flow spending and of the total adaptation costs (as a percentage of GDP) from Agrawala et al. (2011). Calibration was performed over ten decadal periods, since these are the results given in other studies and the results on which we focus in this paper.

To demonstrate the results of the calibration, we compare the relative ratio of stock to flow adaptation investment from the models over time, and on an NPV basis as a percentage of global GDP. (The relevant figures are presented in the Online Resources). Our results reproduce qualitatively those from Agrawala et al. (2011), particularly the relative shares of flow vs. stock adaptation and the NPV of stock and flow adaptation spending levels in the mitigation and adaptation scenario. The numerical differences are primarily a result of our assumption of diminishing marginal returns in the stock adaptation production function. This assumption has the effect of making stock and aggregate adaptation more costly (equivalently, less productive for the same levels of expenditures). As a result, our model solution has lower aggregate adaptation, slightly higher mitigation, and slightly higher net damages. However, the patterns over time and the relative ratios of stock and flow adaptation, and mitigation are essentially the same. We focus on the relative allocation in the analysis below.

Before moving to the impact of alternative assumptions, we here present the results of our model under the reference assumptions. Figure 1 depicts the optimal levels of adaptation of both types and of mitigation over time, for three scenarios: mitigation only ($M^*,A=0$), adaptation only ($M=0,A^*$), and mitigation and adaptation (M^*,A^*). In this and other figures, the level of adaptation means the fraction of damages adapted away, and the level of mitigation means the emissions control rate. Although mitigation and adaptation are not directly comparable in this way as their respective scales measure different processes, intra-policy comparisons across scenarios can be made. The net benefits of stock adaptation are always higher than those of flow adaptation in the reference case, due to the longer lifespan of the stock investment, which results in higher levels of implementation. The pattern of adaptation and mitigation across the three scenarios indicate that the two policies do act largely as substitutes. Additional results in the Online Resources show that the policy costs of all responses to climate change (both types of adaptation plus mitigation) remain small when compared to both the damages that they eliminate as well as the damages that they cannot eliminate.

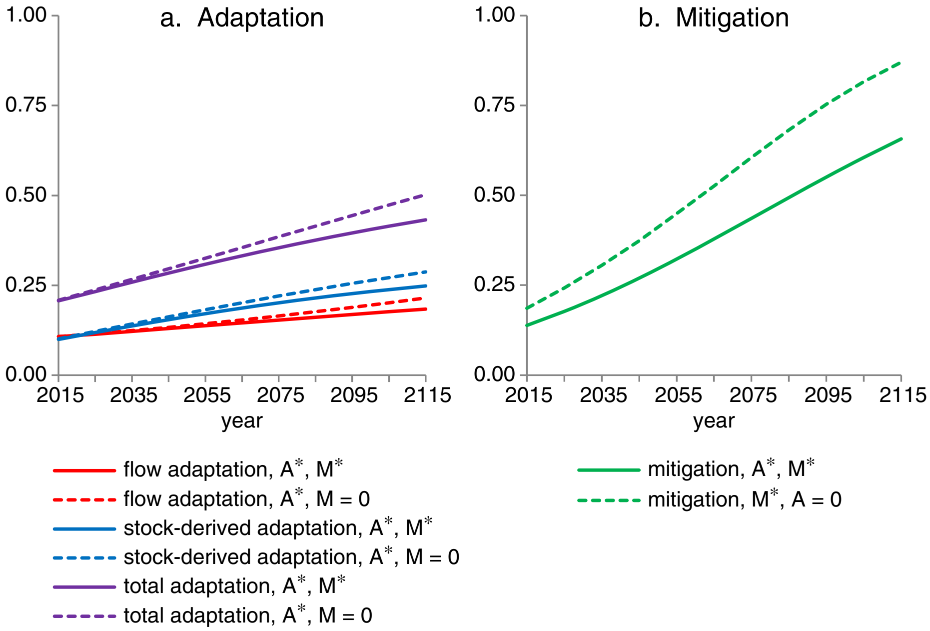

Fig. 1 Comparison of reference case optimal policy levels for adaptation (a) and mitigation (b) over three policy scenarios

4 Impact of parameters on the optimal portfolio

Our focus here is on exploring the assumptions that drive the *relative* level of effort across mitigation and adaptation, a critical issue for national and international climate policy discussions. We demonstrate below the impact of varying three critical assumptions of the model: 1) the shares of flow and stock adaptation in the adaptation production function; 2) the elasticity of substitution between flow and stock adaptation; and 3) the existence of limits to the ability of flow adaptation to reduce damages. Other parameters have been tested, including climate sensitivity and discount rates, and these sensitivity results are given in the Online Resources.

4.1 Shares of flow and stock adaptation inputs in the adaptation production function

In Equation (8), β is the relative share of flow adaptation in the total adaptation production function. Climate change creates a range of damages over different economic sectors, damage types, and localities. For the policymaker choosing levels of flow- and stock-type adaptation funding, β is the proportion of those damages that are best addressed with a short-term (flow) response. Very different mixes of flow adaptation, stock adaptation, and mitigation result from assuming that the climate damages are more amenable to reduction by stock adaptation (β=0.2) or that the damages are more responsive to flow adaptation (β=0.8), relative to the reference case (β=0.49).

Figure 2 shows adaptation policy levels over these three values of β, as well as five inter-adaptation elasticities of substitution. On the right are the NPVs of policy costs as a share of total climate policy spending, with 3 % simple discounting for the purpose of illustration. Focusing on the input share, the relative impact of changing β on flow and on stock adaptation are similar in magnitude and opposite in sign. Adaptation from stock is highest when damages

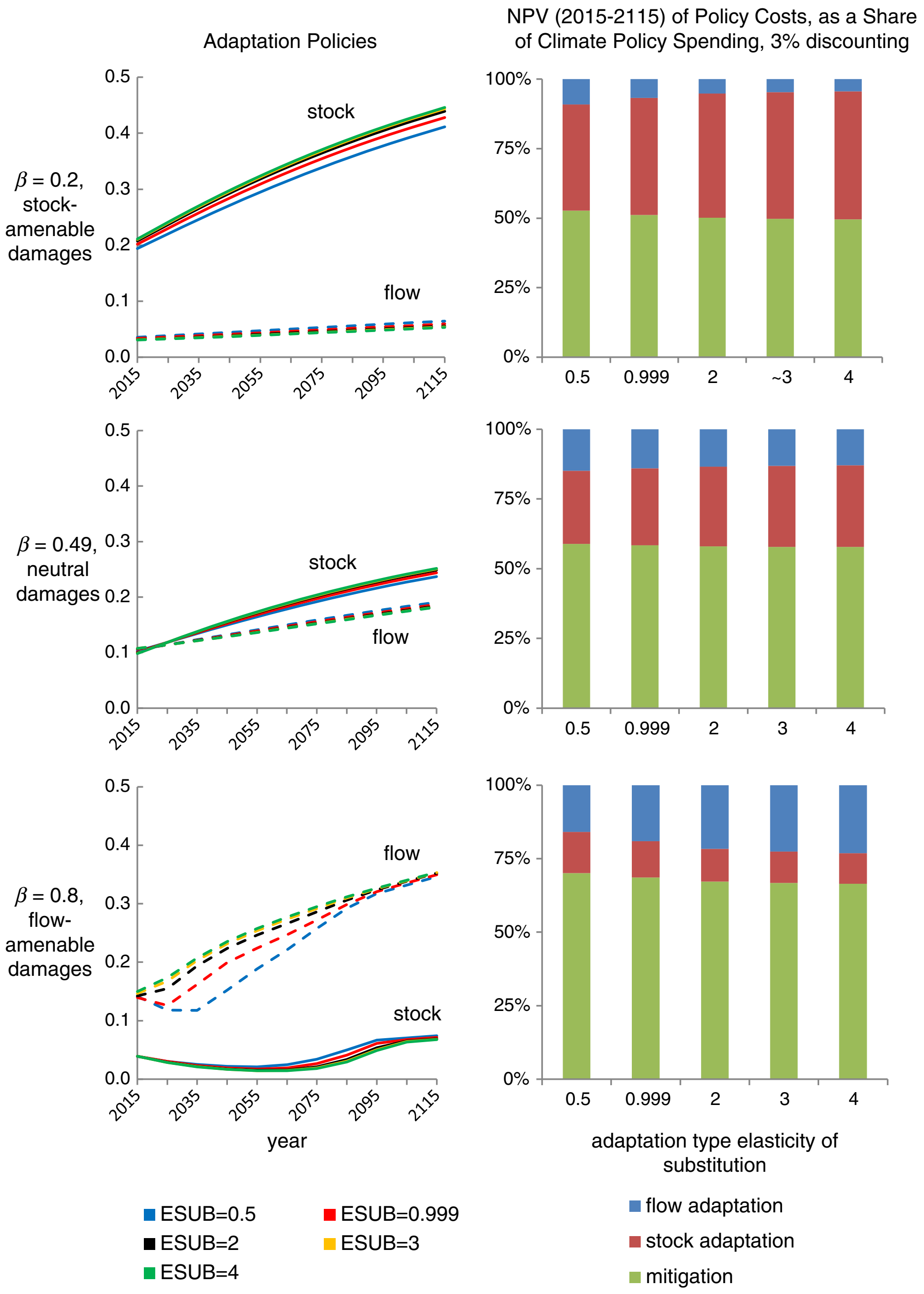

Fig. 2 Levels of adaptation derived from flow and stock investments, over three adaptation share allocations β and five elasticities of substitution σ between adaptation types, and the resulting policy costs with mitigation

are amenable to that type of response and adaptation from flow spending is highest in the opposite case. Total adaptation is highest when damages are lowered most effectively by stock adaptation, rather than by flow adaptation or an equal mix of responses. Mitigation levels are increased when total adaptation is decreased, and therefore are affected by the relative allocation of stock versus flow adaptation; mitigation also has the largest share when flow adaptation is dominant.

4.2 Elasticity of substitution between adaptation types

In practice many climate damages could be alleviated by either a stock- or a flow-type response, suggesting some interchangeability between adaptation technologies. The elasticity of substitution, σ derived from Eq. (8), represents the ease with which one type of adaptation can substitute for the other while keeping the output of the total level of adaptation services constant, and Fig. 2 also shows adaptation policy levels over a range from relatively inelastic (σ=0.5) to very elastic (σ=4). Results show that in general, the relative mix of responses is driven more by the production shares than by the elasticity of substitution. However, the effect of substitutability on the optimal mix is greatest when adaptation is predominantly achieved through flow-type investments (β=0.8), or predominantly stock investments (β=0.2). The effect of substitution is negligible when relatively equal shares of flow and stock adaptation are effective. Increased substitutability between the two adaptation strategies can better promote the use of stock adaptation when the type of damages are best alleviated by stock adaptation (i.e., has a larger share), and can better promote flow adaptation when it has a larger share, at least in early years.

4.3 Capacity limits of flow and stock-derived adaptation

Adaptation responses may have maximum capacity limits that depend on the technology that is applied and the type of damages, among other factors (Adger et al. 2009; Dow et al. 2013). Of particular concern to climate policy and adaptation planning is that many of the flow-type responses (e.g., beach renourishment or increased irrigation) are likely to cease being effective as the impacts of climate change grow larger. De Bruin and Dellink (2011) investigate different types of restrictions on aggregate adaptation. Here we explore the impact on both mitigation and stock adaptation levels of a binding and relatively low limit on the effectiveness of flow adaptation. (Results for a binding limit on stock adaptation were also obtained but are unreported here as the policy lessons suggested were qualitatively similar to those for limited flow adaptation). We denote an adaptive capacity limit with the parameter Λ, which represents the level of climate damages for which flow adaptation fails to alleviate any more additional damages. Expressed as an absolute level of damages, rather than as a rate or percentage of adaptive capacity, the limit marks a technological rather than an economic upper bound on flow adaptation effectiveness. Thus the threshold may be reached at different points in time along the sequence of policy decision periods, depending on the use of alternate policies to substitute for flow adaptation. When the previously unlimited flow response strategy is constrained, the optimizing policymaker will reallocate policy resources among the remaining stock adaptation or mitigation options, or alternatively tolerate higher levels of suffered net damages.

The impacts of a limit on flow adaptation effectiveness on the mitigation and adaptation portfolio are shown in Fig. 3, for several combinations of values of adaptation production share β and elasticity of substitution σ. The results in the absence of limits on flow adaptation are the same as above, shown here for comparison purposes. When flow adaptation is limited its implementation drops rapidly after the capacity threshold is reached (left column), and the rate of decrease is independent of the degree of substitutability. The question then is how the other two responses—whether it is the non-limited stock adaptation alternative or mitigation—can compensate for the limited flow adaptation. Results show that first, in all scenarios, a limited

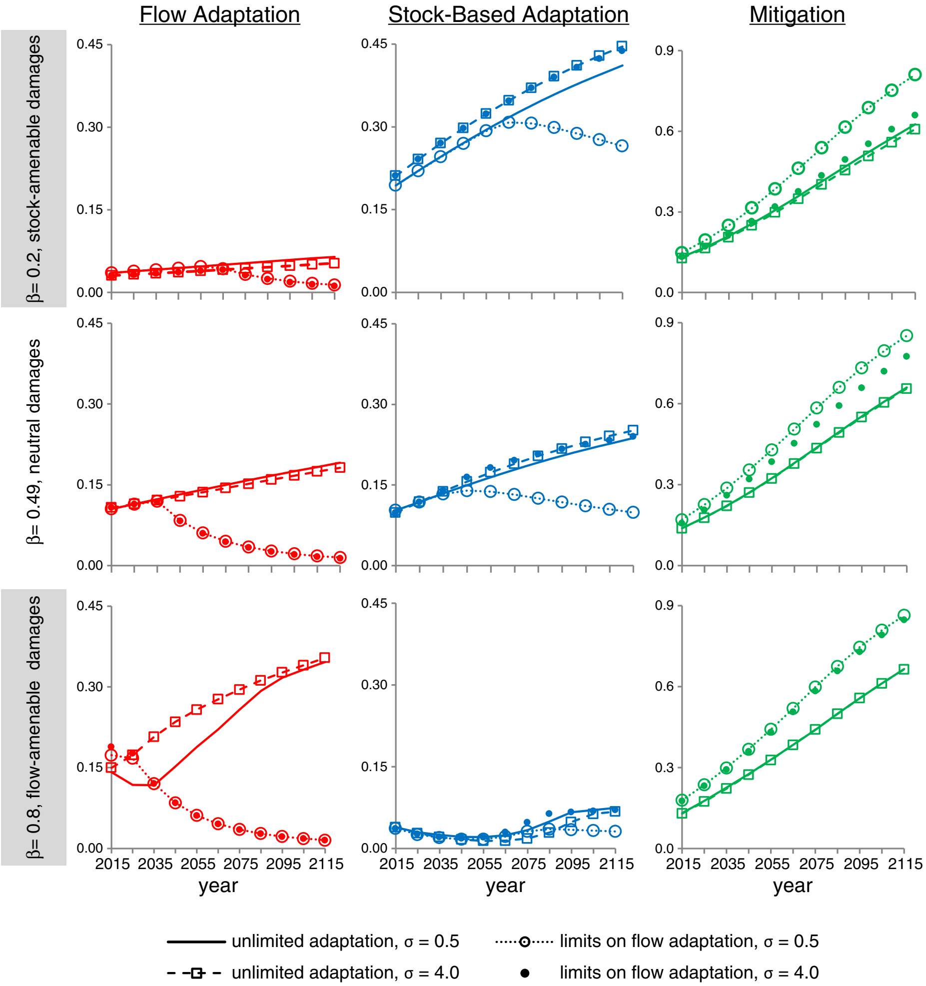

Fig. 3 The effect of flow adaptation limits on the levels of flow adaptation (*red*), stock-derived adaptation (*blue*), and mitigation (*green*). Results are for both low and high elasticities of substitution (σ=0.5, 4), and three factor share allocations (β=0.2, 0.49, 0.8)

flow adaptation causes the optimal level of mitigation to increase to partially compensate for lower total adaptation levels. Second, the unlimited stock adaptation alternative can compensate for limited flow adaptation, but only very slightly and only with a high inter-adaptation elasticity of substitution (σ=4). If this substitutability is low (σ=0.5), stock-derived adaptation levels actually drop in relation to flow adaptation reaching its limit. Mitigation and adaptation act as substitutes; the more aggregate adaptation decreases once a limit is reached, the more mitigation investment is increased to compensate.

A broad range of allocation of investment across mitigation, flow, and stock adaptation could be optimal. The precise mix depends critically on the factors explored here: the relative share of stock vs. flow, the elasticity of substitution, and the existence of limits on flow adaptation. Figure 4 summarizes the range of policy cost shares as a percentage of total climate policy spending in NPV terms (with 3 % simple discounting as before), as explored in Fig. 3.

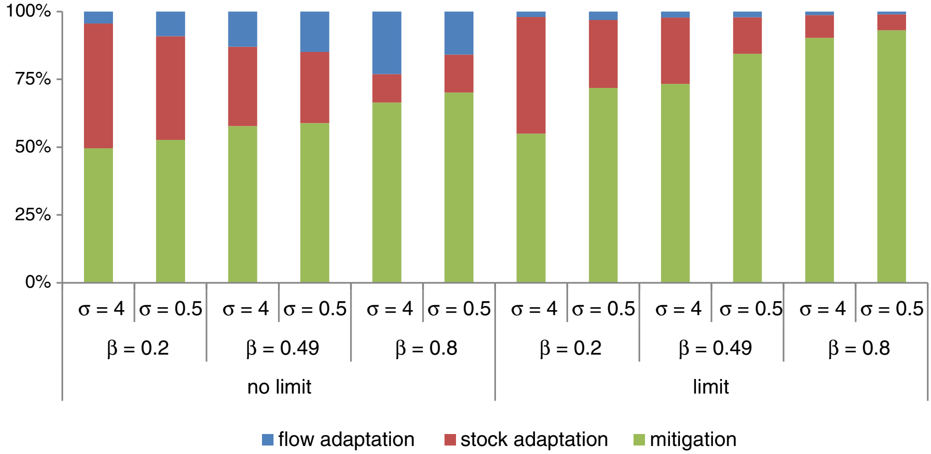

Fig. 4 NPV (2015–2115) of policy cost shares as a percentage of total policy spending. Results are over the 12 scenarios of Fig. 3, with 3 % discounting

In all scenarios, mitigation takes up roughly half or more of all climate change spending over the next century. In general, mitigation tends to act as a substitute for stock adaptation, increasing its share when stock's share is smaller. The intuition is that stock adaptation, with its long lifetimes, better approximates the long benefits payback period of mitigation than does transient flow adaptation. Flow adaptation comprises the majority of aggregate adaptation spending only when it dominates as an input factor share (β=0.8) and when this adaptation is unlimited. In all other cases, the optimal response is to allocate the bulk of adaptation funding to stock adaptation. The role of flow adaptation is also small, as spending on it makes up less than 10 % of all climate policy spending in two-thirds of the scenarios explored.

5 Discussion and conclusions

We have presented results from a model that disaggregates adaptation to climate change into short-lived flow spending and long-lived adaptation stock investments, and models these policy options along with mitigation. This approach explicitly represents the heterogeneity of dynamic characteristics across adaptation activities. Building on de Bruin et al. (2009), we extend ongoing efforts such as Agrawala et al. (2010, 2011) and de Bruin (2011) to improve the usefulness of IAMs in informing public policy decision making by demonstrating the general behavior of different types of adaptation vis-à-vis mitigation. The results are illustrative, but demonstrate that the tradeoffs between mitigation and adaptation depend critically on the composition of heterogeneous adaptation activities, especially their dynamic properties.

Within this modeling framework the key contribution and research objective of this paper is to identify the assumptions that most impact the critical policy question of how efforts should be allocated between adaptation and mitigation. As we have shown, this question cannot be answered without some distinction between short-term and long-term adaptation activities. We have demonstrated that the relative ratio of flow adaptation, stock adaptation, and mitigation depend critically on interactions among: 1) the relative effectiveness in the baseline of stock versus flow adaptation, 2) the degree of substitutability between stock and flow adaptation types, and 3) whether there exist physical limits on the amount of damages that can be reduced by flow-type adaptation investments. The results indicate where more empirical research on adaptation could focus to best inform near-term policy decisions, and provides a first step towards considering near-term policies that are flexible in the face of uncertainty.

First, the optimal combination of stock and flow adaptation responses depends strongly on the mix of climate damages that are faced, and which ones are more amenable to either a stock or a flow response. We find that large variation in stock and flow implementation occurs with changes in the input factor shares. "Incorrect" adaptation choices could be made if, for example, investments are made in long-term stock adaptation when the damages faced are better suited to a flow response. Uncertainty over exactly what type of adaptation is needed for the damages experienced will resolve itself over time, but this could result in reversals in strategy emphasis, i.e., from a stock- to a flow-dominated damage reduction approach, or vice versa.

Second, as empirical estimates of the elasticity of substitution between adaptation types within the aggregate adaptation production function do not exist, the substitutability of short versus long-term adaptation responses is an open question. While the effect of adaptation input factor shares dominates, we find that higher substitutability between the two adaptation strategies promotes the use of stock adaptation when the type of damages are best alleviated by stock adaptation, and promotes flow adaptation in the opposite case, but primarily in early years. In the absence of adaptation limits, our results suggest that a higher elasticity of substitution would allow adaptation activities to more easily compensate for each other.

Third, potentially strong effects on the optimal levels of other climate policies result when the capacity of flow adaptation response is reached. This in turn will require substitution with other policies, either with other available adaptation or mitigation, with new responses that have yet to be developed and tested, or with higher levels of suffered damages. Unlimited stock adaptation alternatives can compensate for limited flow adaptation, but only very slightly and only with a high inter-adaptation elasticity of substitution. Uncertainty over both the existence of a capacity limit on flow adaptation as well as how quickly that limit may approach (in the presence of certain unlimited stock adaptation), would likely increase the level of optimal mitigation and stock adaptation policies in advance of when the limit is breached in a later period.

Given the importance of these three uncertainties, further research into the ability of policymakers to enhance adaptation flexibility may have the potential to improve policy outcomes. This means increasing the substitutability of adaptation activities under different levels of climate damages, or better understanding how to increase the effective range of adaptation. The ability to substitute between the two adaptation types, while constrained by technological factors specific to a damage sector, may be more receptive to human influence. The tradeoffs demonstrated here between adaptation and mitigation, and among different adaptation types, may be different and perhaps even more important in the context of sequential decision under uncertainty. In the real world, policy responses are chosen under uncertainty and revised periodically to respond to new information. Because the uncertainties that affect the amount of mitigation and adaptation will be reduced at different rates, via different mechanisms of resolution, near-term policy may need to hedge more towards one policy response. A full stochastic dynamic analysis is left for future study. The approach undertaken here points to the next step of more fully understanding how policymakers can balance among several climate responses in the near term under uncertainty.

In the absence of a formal stochastic analysis, the results of this study are suggestive for near-term policy. In particular, given the significant uncertainties in future climate change and the relative effectiveness of policy responses, near-term efforts should certainly consist of a healthy mix of all types of possible investments. Mitigation, flow adaptation, and stock adaptation should all be explored in the near term in order to reduce the uncertainty in the range of damages for which they are effective. While the uncertainty in future climate damages may not be reduced appreciably anytime soon, we have more control over what we learn about the cost and effectiveness of different responses. Reducing these uncertainties will aid future policymakers in adjusting policies in what is sure to be a long-term process of coping with climate change.

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