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The Economics of Adaptation

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Deliverable 2.1: Defining the opportunity costs of adaptation

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Deliverable number	D2.1
Work Package Number	2
Submission date	November 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Defining the opportunity costs of adaptation
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Date:	November 2016
Contact details	Alistair Hunt, ecsasph@bath.ac.uk
Work Package Number	WP2
Deliverable number	D2.1
Filename:	Deliverable 2.1 Final .doc
Document history:	Draft/ Final and version number
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

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Introduction

Deliverable 2.1: Defining the opportunity costs of adaptation

This deliverable is designed to provide methodological advances in the treatment of trade-offs in resource allocation between adaptation and other objectives such as wider economic development and GHG mitigation. These advances allow analysts undertaking economic assessment of adaptation to more effectively delineate the costs and benefits of potential alternative resource allocations. In so doing, the optimal balance between alternative allocations can be identified. There are four specific sub-tasks within this task.

Sub-task 1. Defining the relationship between development and adaptation.

Sub-task 2. Evaluating investment in sector-specific adaptation relative to system-wide adaptation.

Sub-task 3. Modelling the mitigation – adaptation decision framework

Sub-task 4. Preference-based evaluation of trade-offs between different forms of adaptation

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Authors: Alistair Hunt

Deliverable number:	D2.1
Work Package Number:	2
Submission date:	30.11.2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	**Defining the relationship between development and adaptation**
Authors:	Authors: Alistair Hunt
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Date:	Submission Date
Contact details	Name, email of lead author
Work Package Number	WP
Deliverable number	D2.1
Filename:	.doc
Document history:	Draft/ Final and version number
Type of Activity	RTD
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1 Introduction

Information about the size of resource costs and benefits associated with adapting to climate change – additional to those associated with non-climate, development objectives – is recognised as being useful for a variety of reasons. Chief among these is that the size of the addition provides an immediate indication of the extent of the potential financial commitment that would be required by those responsible for implementing the adaptation measure. Similarly, an aggregate measure of adaptation costs may scope out the size of the budgetary commitment that a public authority may face, or that needs to be leveraged from private finance.

Callaway and Hellmuth (2006) identify further reasons as to why a decomposition of adaptation costs and benefits from development costs and benefits may be useful. They highlight the fact that in many countries and regions data on weather and climate do not exist or are not easily accessible by the population that would potentially use this information for planning purposes. However, demonstration of the usefulness of such data in informing the allocation of scarce economic resources may encourage investment in its provision.

An additional reason for decomposing adaptation cost/benefit data is that the data can be shown to differ in its interpretation depending on the main objectives and perspective of the analyst. Specifically, the fact that competing economic actors have different objectives, perhaps reflecting different public responsibilities or priorities, may mean that the phasing of any investment that has both development and adaptation benefits will be influenced by these priorities. For example, whilst a water company will have as its priority the effective meeting of its customers' water consumption needs, a water planning authority may be more concerned with the risk of climate change to projected water supplies. As a consequence, the net economic benefits of the investment may differ according to the analyst's perspective. This may give rise to confusion and misunderstanding if competing economic actors are appraising a contentious scheme. A clear presentation of the decomposed data then serves to increase the transparency of appraisals, thereby reducing the risk of misunderstanding and conflict.

This paper aims to illustrate the extent that the benefits of benefit/cost decomposition can be realised by adopting the tabular approach of Callaway and Hellmuth (2006). Similar to that paper, a real-world example is used to highlight these benefits. This paper also looks to explore how the approach of Callaway and Hellmuth can be developed to incorporate other aspects of the economics of adaptation, including uncertainty.

Below, section 2 outlines the method adopted in this exercise, primarily based on that adopted by approach of Callaway and Hellmuth. Section 3 then provides a worked example centred on a housing development planned in the East of England but potentially vulnerable to increasing coastal flood risks under climate change scenarios.

2 Methods

Callaway and Hellmuth (2006) set out a table that summarises the welfare changes – i.e. the net economic benefits – that result from implementing responses to alternative combinations of development and climate change drivers. The structure of the table is reproduced below.

The level of response – i.e. adaptation, A – to development and/or climate change is indicated on the left of each quadrant. This adaptation is assumed to take place prior to the level of development being decided and the level of climate change becoming known. In order to decompose the welfare changes associated with these two drivers, one is kept constant at its baseline level whilst the other is varied. Thus, in the top quadrant, climate is kept constant at C0, whilst the level of development varies between its baseline level, D0, i.e. no development, and a new level, D1. Adaptation, A, is assumed to be sufficient for development level, D0 in the first row, development level D1 in the second row. Resulting welfare levels are indicated as E1 – E4.

Conversely, in the second quadrant, development is kept constant at D0, whilst some climate change, C1, is contrasted with no climate change, C0, and levels of adaptation are appropriate to C0 in the first row and C1 in the second row. Resulting welfare levels are indicated as E5 – E8.

Finally, the welfare effect of responding to the combination of changes in both drivers is shown in the bottom quadrant. Levels of adaptation are appropriate either to D0 or D1, in the top and bottom rows, respectively. Resulting welfare levels are indicated as E9 – E12.

It should be noted that whilst the levels of change in climate and development are characterised here as being from a baseline defined as the current time period, the time dimension and the degree of change can be generalised without any loss of applicability. Thus, for example, the two levels of climate, C_0 and C_1, could equate to two alternative climate scenarios in 2040.

Adjustment to Development	No Development & Existing Climate: D_0, C_0	Development & Existing Climate: D_1, C_0
Adjusted to D_0: **A [C_0, D_0]**	Optimal adaptation to no development **E_1**	Sub-optimal adaptation to development **E_2**
Adjusted to D_1: **A [C_0, D_1]**	Sub-optimal adaptation to no development **E_3**	Optimal adaptation to development **E_4**
Adjustment to Climate	**No Development & Existing Climate: D_0, C_0**	**No Development & Climate Change: D_0, C_1**
Adjusted to C_0: **A [C_0, D_0]**	Optimal adaptation to existing climate **E_5**	Sub-optimal adaptation to climate change **E_6**
Adjusted to C_1: **A [C_1, D_0]**	Sub-optimal adaptation to existing climate **E_7**	Optimal adaptation to climate change **E_8**
Adjustment to Development and Climate	**Development and Existing Climate: D_1, C_0**	**Development and Climate Change: D_1, C_1**
Adjusted to D_1, C_0: **A [C_0, D_1]**	Optimal adaptation to development & existing climate **E_9**	Sub-optimal adaptation to climate change, and optimal adaptation to development **E_{10}**
Adjusted to D_1, C_1: **A [C_1, D_1]**	Sub-optimal adaptation to exiting climate, and optimal adaptation to development **E_{11}**	Optimal adaptation to climate change and optimal adjustment to development **E_{12}**

Development States D_0; D_1; Current Climate, C_0; Future Climate, C_1

The table highlights the fact that there are often different objectives to account for when planning responses, and that achieving these objectives leads to future impacts on social welfare that are uncertain. Comparison of the results serves to demonstrate the extent to which uncertainty may lead to the wrong amount of adjustment, as for E2, E3, E6 and E7. Furthermore, the decomposition of the influence of these factors on welfare may make explicit their relative importance. The example in section 3 below illustrates this.

3 A Worked Example

We provide a worked example of the Callaway-Hellmuth grid, based on real-world data in the flood context. The example is derived from data assembled in a recent discussion as to whether a town could accommodate increased housing provision in the face of increased coastal flood risk.

Background

The (fictitious) Borough of Broadchurch is located in south-east Dangenshire, on the East Coast of England, and has a population of 56,000. Currently, Broadchurch has a large proportion of its population employed in low-skilled, low-value jobs in agriculture and associated industries. There are plans for economic re-generation of parts of Broadchurch, focused on the High Street and town centre area. In order to support economic regeneration, there are plans for housing growth in the Borough. The Regional Spatial Strategy (RSS) allocates 2,750 new houses per annum until 2021 and the Borough Council has a responsibility to ensure that there are sufficient sites to accommodate this housing development.

Broadchurch is at risk of tidal flooding. Broadchurch Borough Council's Strategic Flood Risk Assessment (SFRA) has classified the Borough into three categories of flood risk. The town centre and other parts of the town earmarked for development are in areas categorised as high risk. The risk of tidal flooding in Broadchurch will increase with climate change. On the east coast of Britain, the risk of tidal flooding due to sea level rise is compounded by the long term geophysical movement of the British land mass, which is sinking relative to mean sea level in the North Sea. The standard of protection (SoP) afforded to Broadchurch by its flood defences will decrease over time as sea levels rise (assuming no improvements are made). Currently, the Broadchurch defences provide a SoP of 1 in 100 years. By 2020, the SoP drops below 1 in 100 years to 1 in 65 years and by 2050 this is reduced to 1 in 13 years. The defences will require heightening if they are to continue giving protection against a 1 in 100 year event.

Consequently, the Environment Agency (EA) for England & Wales expressed concern over the proposed development in Broadchurch due to the increased risk of tidal flooding caused by climate change. The EA anticipates increasing costs associated with defending the Dangenshire coast at Broadchurch from tidal flooding. The EA argues against the housing development proposed by Broadchurch Borough Council (BC), highlighting that the development will increase the likely population at high risk of flooding. The BBC argue that the cost of maintaining and improving flood defences should be weighed against the cost of inhibiting development in Broadchurch.

Analytical framework

To help resolve the difference of opinion between Broadchurch BC and the Environment Agency it is necessary to appraise the housing development and the associated economic regeneration of the area taking account of future flood risks. Part of this appraisal involves economic analysis in which the advantages and disadvantages are, as far as possible, expressed in monetary terms. The question to explore is whether the planned housing development yield a net social benefit in future worlds defined by climate change.

There are a number of direct and indirect advantages and disadvantages associated with (re)development and building flood defences. These are outlined in the table below; indirect advantages or disadvantages for the town of Broadchurch are in italics.

Table 1 Advantages and Disadvantages of Re-development in Broadchurch

Redevelopment		No Redevelopment	
Disadvantages	**Advantages**	**Disadvantages**	**Advantages**
Financial costs of new development	Eases housing shortage	*No economic regeneration*	No increase in value at risk from flooding
Increase in value at risk from flooding	*Economic regeneration*	No easing of housing shortage	Avoid financial costs of new development

Table 2 Advantages and disadvantages of building flood defences in Broadchurch

Flood Defences		No Flood Defences	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
	Reduced risk of tidal and storm surge flooding	No increase in SoP for existing properties	
Financial costs of building flood defence	Increased standard of protection (SoP) for existing properties	No increase in SoP for new properties	
Residual risk of flooding	Increased SoP for new properties	Increasing risk of flooding in future due to climate change	
	Decrease in insurance premiums	*Increase in insurance premiums*	Avoid financial cost of building defences

The subsequent economic analysis quantifies these costs and benefits as far as possible. The baseline against which the welfare change is measured is assumed to be where no adjustment (adaptation) is made. The resulting net benefit estimates are presented below in the Callaway-Hellmuth matrix.

Results

The upper quadrant shows the welfare changes – measured in net present value terms - when no climate change is assumed, when development may or may not go ahead, and with two levels of adaptation. It should be clear that welfare is increased by proceeding with the development; indeed, the benefits of development are positive in the absence of any adaptation to such development, (E^2 - E^1= €30m). However, the net benefit of adaptation to development is positive, (E^4 – E^2 = €30m), and the optimal solution in the absence of climate change is to proceed with development, and to adapt to that development (E^4). In other words, the benefits of building new housing in Broadchurch are further increased if flood protection is provided for this housing.

The effects of climate change on welfare in the absence of development are considered in the middle quadrant. A failure to adapt to climate change is shown to have a negative effect on net welfare, (E^6), as is adaptation when climate change does not occur, (E^7). Thus, the welfare change, E^6 – E^5, denotes the cost of climate change, C^1 – C^0, with a level of adaptation to C^0. However, adjusting to climate change C^1 does have a net positive effect on welfare (E^8).

When both development and climate change are considered together – as in the bottom quadrant – it is clear that adapting to the right level of adaptation is important. If it is assumed that climate change will be at C_1, matched by adaptation to this level, but it actually turns out to be C_0, the welfare change is €-10m, (E^{11}), whilst if climate change turns out to be C_1, the welfare improvement is €65m (E^{12}). Alternatively, if it is assumed that climate change will be at C_0, matched by adaptation to this level, but it actually turns out to be C_1, the welfare change is €40m, (E^{10}), whilst if climate change turns out to be C_0, the welfare improvement is €60m, (E^9).

Table 3 Defining the relationship between development, climate risk and adaptation: Broadchurch NPVs under alternative development-climate risk adaptation scenarios

(30 yr time horizon, 3.5% discount rate; E = €M)

	Development States (Current Climate, C_0)	
Adjustment of Flood Defences to Development	**No Development: D_0**	**Development: D_1**
Adjusted to D_0: A [C_0, D_0]	$E^1 = 0$	$E^2 = 30$
Adjusted to D_1: A [C_0, D_1]	$E^3 = -20$	$E^4 = 60$
Adjustment of Flood Defences to Climate	**No Development & Existing Climate: D_0, C_0**	**No Development & Climate Change: D_0, C_1**
Adjusted to C_0: A [C_0, D_0]	$E^5 = 0$	$E^6 = -10$
Adjusted to C_1: A [C_1, D_0]	$E^7 = -10$	$E^8 = 20$
Adjustment of Flood Defences to Development and Climate	**Development and Existing Climate: D_1, C_0**	**Development and Climate Change: D_1, C_1**
Adjusted to D_1, C_0: A [C_0, D_1]	$E^9 = 60$	$E^{10} = 40$
Adjusted to D_1, C_1: A [C_1, D_1]	$E^{11} = -10$	$E^{12} = 65$

Within the context of this case study, there are a number of questions that the table can help to answer. Perhaps of most relevance is whether $E^{12} \geq E^8$ and $E^9 \geq E^5$. The first comparison seeks to shed light on whether the net social benefits of the planned housing developments - with flood defences optimally adjusted to both the level of development and climate change - greater than the net social benefits with no housing development. The second comparison focuses on the net benefits of the development without climate change. The Broadchurch BC believes that the net benefits will be positive and high, whilst the EA questions this belief. The results in this table would suggest that it is indeed the case that development with appropriate adaptation does result in net social benefits, with or without climate change.

The EA would, however, also be interested to see that, as noted above, there are significant costs associated with maladaptation, (i.e. adaptation to the wrong level of climate change), when development proceeds since E^9 - E^{10} = -€20m and E^{11} - E^{12} = -€75m, when low and high levels of adaptation are undertaken, respectively. In the instance that development does not proceed, the potential maladaptation costs are E^5 – E^6 = -€10m and E^7 – E^8 = -€30m, when low and high levels of adaptation are undertaken, respectively.

It should be noted that the data required to estimate the welfare changes can be used to derive further useful indicators. For instance, the EA is likely to be very interested in the absolute costs of adaptation with, and without, development, given the budgetary implications this is likely to have for the organisation in the absence of any cost-sharing with the Broadchurch BC. The incremental cost of adapting to climate change, with, or without, development is also of interest to the EA (i.e. the costs of moving from E^9 to E^{12} and from E^5 to E^8, respectively) since it may provide an indication as to the scale of expenditure increase that climate change-induced coastal flooding could induce in other comparable locations.

4 Discussion

In the preceding sections, the matrix developed by Callaway and Hellmuth (2006) has been applied to a European coastal flood context. It provides a visual presentation of the ex ante net welfare changes, (equivalent to net economic benefits, measured in net present value terms), associated with alternative levels of adaptation under varying development and climate scenarios. The quantitative results then provide a transparent data-set with which to inform stakeholder negotiations and decisions.

There are a number of discussion points that arise from this exposition.

1. *Representation of uncertainties*. The two-by-two matrix form clearly simplifies and reduces the range of development and climate scenarios considered in the table. It is relatively straightforward and acts as an understandable form for communicating the types of choices to be made. However, in principle, there is no reason for the dimensions of the matrix to be enlarged to include a wider range of development/climate scenarios.

2. *Treatment of uncertainties*. As indicated in the Results section above, the matrix does not – of itself – provide the means with which to evaluate the data and make subsequent adaptation investment decisions. However, in so far as the scenarios selected are representative of the range of those considered plausible, the matrix provides the intermediate output necessary to inform decisions that utilise economic criteria. In doing so, it highlights the potential extent of mal-adaptation, i.e. when the level of adaptation is not well-aligned to the level of development or climate change that transpires.

3. In order for the EA and the BC to make a decision as to what action should be taken next, they need to consider the following conclusions that can be drawn from the date:

    - The Council can argue that development is beneficial whether climate change occurs or not, (E9, E10), and even in the absence of flood adaptation to development and/or climate risks (E2).

    - The EA establishes that as long as development proceeds, it is worth adapting to development, whether or not climate change occurs (E4, E10, E12).

    - The EA establishes that in the absence of development, there is a risk of either over- or under-adaptation to climate risks that will result in a welfare loss (E6, E7).

    - A welfare loss would also occur if the EA adapts to the development that does not then occur (E3) in the absence of climate change.

    - If development is assumed to proceed, a welfare loss will result if the EA over-adapts to climate change risk (E11).

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Chapter Two: Framework for the evaluation of system-wide adaptation actions relative to sector-specific adaptation actions

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Deliverable number:	D2.1
Work Package Number:	2
Submission date:	30.11.2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	**Framework for the evaluation of system-wide adaptation actions relative to sector-specific adaptation actions**
Authors:	James Pardy and Alistair Hunt
Other Contributors	Other Contributors
Date:	Submission Date
Contact details	Name, email of lead author
Work Package Number	WP
Deliverable number	D
Filename:	.doc
Document history:	Draft/ Final and version number
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
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1 Introduction

The framework presented in this paper aims to support the broadening of actions considered by decision makers for adapting to climate change and variability. It divides the set of adaptation actions into two types: sector-specific and system-wide. These two categories follow the UKCIP's (2007) definitions of options for planned adaptation; sector-specific actions are related to Delivering Adaptation Actions (DAA) and system-wide actions are related to Building Adaptive Capacity (BAC) actions.

The UKCIP states that "many capacity building actions are also adaptation actions" (2014). This emphasis implicitly suggests that system-wide actions are not the obvious choice for adapting to climate change and variability. It is this potential for underrepresenting system-wide actions in the adaptation discourse that motivated this framework. By clarifying the benefits and costs associated with system-wide actions, the framework hopes to better characterise system-wide actions as options for adaptation. Economics, as a decision science, can be used to evaluate these alternative adaptation actions. The terminology and concepts used in the framework are outlined in sections 1.1 to 1.3.

1.1 Definitions

The framework uses terminology associated with both adaptation and economics. This terminology is as generalised as possible, in order to be applicable to a variety of adaptation decision making contexts. The key expressions used in this framework are defined in Table 1. The examples provided are not intended to be exhaustive.

The terminology defined in Table 1 is applied throughout the framework. The concepts that form the basis of the framework are introduced in the following two sections (1.2 and 1.3).

1.2 Adaptation Actions

Adaptation actions are intended to reduce the vulnerability of human and natural systems to climate risks, and to exploit climatic opportunities (OECD, 2011). To date, the literature on adaptation actions has primarily focused on sector-specific actions that directly target specific climate drivers. This is arguably due to the fact that local manifestations of specific climate risks and opportunities often require ad hoc, context specific adaptation actions (Adger and Brooks, 2004; IPCC, 2014a; Tol and Yohe, 2002).

However, another branch of possible adaptation actions, system-wide actions, is available to decision makers. System-wide actions look to build cross-sectoral resilience to climate drivers by changing the adaptive capacity of human and natural systems (IPCC, 2014b; UKCIP, 2014). These actions are characterised by indirect benefits, which may be overlooked if they are not well defined. For example, improved weather forecasts do not mitigate specific climate risks by themselves, but the information they provide can be used to better inform decision makers about actions they should take in response to predicted climate risks.

(Next page: Table 1: Definitions and examples of expressions relevant to the framework (by selected sources).

Expression	Definition	Relevant Examples
Decision Maker	Any agent that has to decide between alternative actions, given the resource constraints they face. In this framework, the alternatives considered are adaptation actions.	Consumers, firms, government bodies, households, policymakers, workers (Lipsey and Chrystal, 2007)
Sector	*"A division or part, a unit"* (OED Online, 2015a). In this framework, a sector faces idiosyncratic and systemic risks and opportunities.	A particular ecosystem, industry, geographical region or population group
System	A set of things working together as parts of a mechanism or an interconnecting network; a complex whole (OED Online, 2015b). In this framework, a system faces systemic risks and opportunities that may impact a range of its sectors.	Human: Communities, economies, households and institutions . Natural: Biological, ecological and geographical
Sector-specific Actions	Practical adaptation actions that aim to reduce the vulnerability of a sector to climate risks, or to exploit positive climatic opportunities (UKCIP, 2007).	Coastal defences, flood defences, irrigation planning, reforestation, resource quotas (IPCC, 2014a)
System-wide Actions	Adaptation actions that aim to reduce the vulnerability of a system to climate risks, or to exploit positive climatic opportunities. They usually involve building institutional coping capacity that will impact a range of sectors (UKCIP, 2007).	Budget revisions, disaster response strategies, early warning systems, education, regulatory frameworks, tax reforms (IPCC, 2014a)
Climate Drivers	Climatic factors that may expose sectors and systems to potentially damaging climate risks and provide positive climatic opportunities (IPCC, 2014b).	El Niño Southern Oscillation, global warming, ozone damage, changes in themohaline circulation (Met Office, 2012)
Non-climate Drivers	Non-climatic factors that may exposure sectors and systems to potentially damaging non-climate risks and provide positive non-climatic opportunities (IPCC, 2014b).	Employment levels, financial and natural resources, governance, resource distribution, social cohesion
Direct Benefits Related to Climate Drivers	Benefits that can be directly attributed to an adaptation action, and are usually easier to identify. Sector-specific actions that target specific climate drivers have more direct benefits than system-wide actions.	Damages avoided and lives saved by flood defences, increased crop yield from improved irrigation, fish stocks sustained by annual quotas
Indirect Benefits Related to Climate Drivers	Benefits that can be indirectly attributed to an adaptation action, and are usually harder to identify. System-wide actions that indirectly target climate drivers are characterised by indirect benefits, which relate to the adaptation actions they facilitate.	Damages avoided by implementing coastal defences in areas known to be at risk of tidal surges, as a result of improved geographical and meteorological information
Adaptive Capacity	Ability of a system to adjust to potential damages, exploit opportunities, or react to consequences of climate change and variability (IPCC, 2014b).	Limiting factors: financial resources, information, institutional structure, technology, perceived risks
Pathway	A period of time over which combinations of climate and non-climate factors are realised. Exogenous and endogenous variables influence climate and non-climate pathways.	Representative Concentration Pathways and Shared Socioeconomic Pathways (IIASA, 2014)

Therefore, decision makers should account for the wider impact of system-wide actions in order to reliably compare them to sector-specific actions. In economics, a failure to account for all the benefits and costs associated with alternative actions can result in a misallocation of resources. For responses to climate change and variability this is known as maladaptation (IPCC, 2014b).

Moreover, system-wide actions may be better suited to achieve wider objectives than conventional adaptation options. The inherently broad nature of system-wide actions will be likely to support non-climate objectives, such as sustainable development, in addition to adaptation and mitigation. For example, improved education in statistics may help individuals better understand climate change data, allowing them to make better-informed decisions about how they should adapt to climate drivers. However, improved education could also be related to the overall development objectives of a society. This type of action is endorsed by the Intergovernmental Panel on Climate Change's climate-resilient pathways (IPCC, 2014d) and the literature on mainstreaming (Chuku, 2009; Mitchell and Tanner, 2006). Therefore, system-wide actions may be better placed to target wider societal objectives than sector-specific actions.

However, the benefits and costs relating to climate and non-climate drivers need to be formally distinguished. This need is driven by the discourse on additionality, which focuses on the separation of the benefits and costs of adaptation actions from mitigation and development (IPCC, 2014d). This is particularly important for overseas development assistance (ODA), where donors want to catalogue how adaptation funds are being used and recipients want adaptation funds "over and above mainstream ODA" (Frankhauser and Burton, 2011). By classifying the benefits and costs relating to climate and non-climate drivers, the framework in this paper addresses these concerns.

As a result, the framework developed here can be used to differentiate between system-wide and sector-specific actions along two spectrums:

1. The extent to which benefits from the adaptation action are directly or indirectly related to climate drivers; and,

2. The extent to which non-climate drivers are targeted by the adaptation action.

These two spectrums are not mutually exclusive, as adaptation actions with more indirect benefits in relation to climate drivers are likely to target more non-climate objectives and vice versa (IPCC, 2014d). Figure 1 illustrates where system-wide and sector-specific actions fall on the combined spectrum.

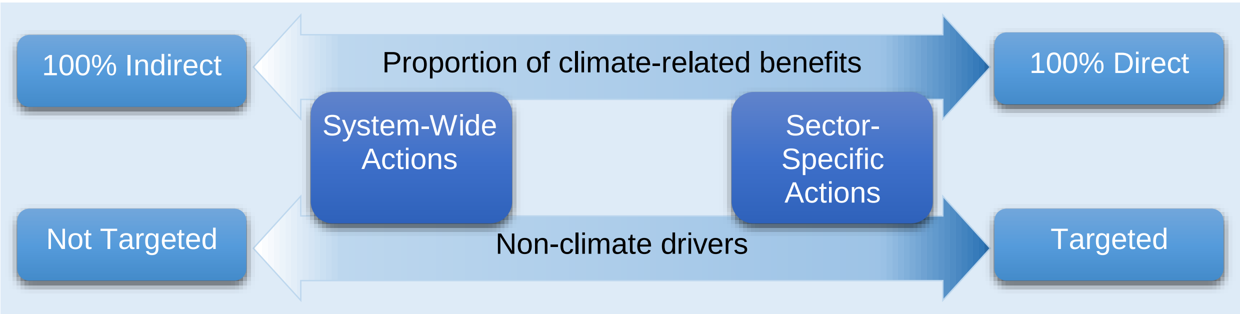


Figure 1: Spectrum for defining system-wide and sector-specific actions. Differentiation between adaptation actions can be achieved through two parameters; the proportion of benefits related to climate drivers and whether non-climate drivers are targeted or not.

Given that all the adaptation actions along this spectrum require economic resources to be implemented, there are implicit trade-offs between the alternatives (IPCC, 2014c). In order to make such trade-offs using economic criteria, we need to know the actions' full benefits and costs. The framework therefore defines the benefits and costs associated with different types of adaptation actions. This is more challenging in the case of system-wide actions where the benefits, in terms of reduced climate risk, are largely incurred indirectly. Therefore, the framework focuses on characterising the indirect benefits of system-wide actions.

1.3 Adaptive Capacity

Adaptive capacity determines the set of feasible adaptation actions, and therefore needs to be considered in more detail. The IPCC defines adaptive capacity as the ability of systems to adjust to potential damages, exploit opportunities, or react to realised consequences of climate change (IPCC, 2014b). The framework developed here focuses on how system-wide actions achieve this by targeting the adaptive capacity of a system.

Tol and Yohe (2002) define eight determinants of adaptive capacity that are relevant to different systems (see Figure 9). The set of feasible adaptation actions depends upon the structure and interaction of these determinants. In economic terms, the determinants of adaptive capacity generalise to the set of resources available in a system and the ability of the system to efficiently use these resources in the pursuit of adaptation (Adger and Brooks, 2004). Therefore, both system-wide and sector-specific actions are a manifestation of the adaptive capacity of a system (Smit and Wandel, 2006). From this, adaptive capacity is similar to a production possibility frontier (see Figure 2).

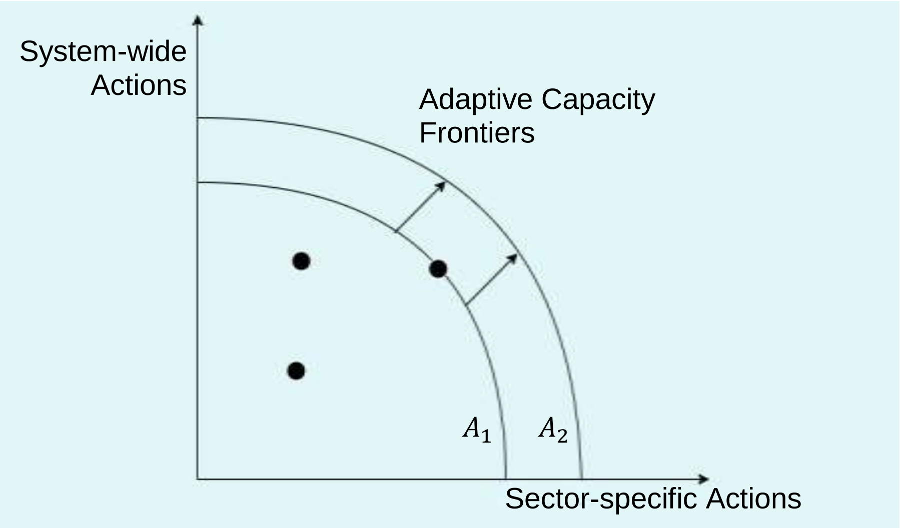


Figure 2: Adaptive capacity frontiers representing short-run adaptive capacity, in relation to the set of feasible sector-specific and system-wide actions. Adaptive capacity frontiers are dynamic in the long-run.

In Figure 2, short-run adaptive capacity is fixed (A_1). This demonstrates the resource constraints posed by adaptive capacity at a given point in time. The dots represent feasible allocative combinations of system-wide and sector-specific actions, which can either be located within or on the adaptive capacity frontier (A_1). Decision makers therefore face trade-offs between sector-specific and system-wide actions in the short-run, and the adaptive capacity frontier represents the opportunity cost between combinations of these actions. However, in the long-run adaptive capacity is variable. System-wide actions look to change adaptive capacity in this dynamic context, by targeting its determinants i.e. the resources and constraints. For example, decision makers could increase the budget apportioned to adaptation actions, pushing the adaptive capacity frontier outwards from A_1 to A_2. In contrast, sector-specific actions do not change adaptive capacity. They directly target climate drivers and remain a reflection of short-run adaptive capacity. For example, the decision to build flood defences is a reflection of the adaptive capacity of a system at a given point in time, as the decision makers were willing and able to convert the resources available to them into the defences. However, the flood defences do not target the resources and constrains of adaptive capacity in a dynamic context. (Williamson et al., 2010).

Economics can be used to evaluate the short-run trade-offs between system-wide and sector-specific adaptation actions. Structuring the problem in a decision making framework helps clarify the relevant concepts, and suggests how a decision maker should define the benefits and costs associated with each adaptation action. Economic decision theory can then be used to recommend choices of actions or strategies, dependent on the context, rules and criteria used. This paper first develops the conceptual framework and considers extensions of this framework (section 2), before applying it to a worked example (section 3) and finally developing practical considerations (section 4).

2 Conceptual Framework

The structure of the conceptual framework builds upon the recent applications of benefit-cost frameworks to adaptation actions developed by Leary (1999), Ranger et al. (2010), and Willows and Connell (2003). In this framework, a decision maker is faced with a set of feasible adaptation actions in a given period. This set is determined the adaptive capacity in that period. The focus is on one system-wide action within this set, which must be evaluated and compared to the alternative actions. The decision maker must decide to take actions that either reduce vulnerability to climate risks or exploit climatic opportunities directly or indirectly. The outcome of the actions they choose depends upon the future climate and non-climate pathways. Therefore, the realised pathway determines the benefits and costs associated with a particular adaptation action. In addition, wider decision objectives can be accounted for, as the benefits and costs related to non-climate drivers are included (IPCC, 2014d).

The framework outlined in section 2.1 is designed to be as generalised as possible, so that it can be applied to a variety of temporal, spatial and social contexts. Therefore, no initial assumptions are made about the degree of uncertainty facing the decision maker, or their preferences towards particular outcomes. The framework incorporates temporal considerations and uncertainty by defining a “decision period”, followed by a “realisation period”. In the decision period the decision maker must choose between the alternative adaptation actions in the feasible set. In the realisation period the climate and non-climate pathway and changes in adaptive capacity are realised, which determines the benefits and costs associated with the chosen adaptation action(s). The length of the time horizon is not specified, although it is envisaged that the time horizon should capture the full benefits and costs associated with the adaptation action(s) under consideration.

The ratio of benefits directly or indirectly related to climate drivers will depend on the type of adaptation action i.e. system-wide or sector-specific. For example, a climate change awareness raising programme is likely to have a higher proportion of indirect than direct benefits related to climate drivers, as the programme itself doesn’t mitigate climate risks or exploit climatic opportunities. In addition, the quantity of benefits and costs related to non-climate drivers is included. This will allow the decision maker to decide whether climate or non-climate objectives are being targeted. The framework then defines the relationship between adaptive capacity and feasible adaptation actions in order to identify the indirect benefits of system-wide actions (section 2.2). Finally, different decision making contexts are evaluated (section 2.3).

2.1 General Framework

In decision *period t,* the system-wide action under consideration is denoted as a_1 and the set of alternative adaptation actions is denoted as a_{J-1}. The set of feasible adaptation actions in *period t* could reflect both the quantity and/or quality of actions the decision maker has to choose from. In this framework, the set of feasible adaptation actions is synonymous with adaptive capacity in *period t*, such that:

$$A_t = \{a_1, a_{J-1}\}, \tag{1}$$

Where:
There are J feasible adaptation actions in period t;
$a_j \in A_t$ is a feasible adaptation action in period t; and,
a_{J-1} contains both system-wide and sector-specific actions.

The time horizon is defined as *period T*. This represents the period over which any benefits, costs, changes in adaptive capacity, and climate and non-climate pathways are realised. The time horizon can take any length, but it should capture the full benefits and costs of the adaptation action(s) under consideration. Up to *period T*, the continuum of possible climate and non-climate pathways is defined as S_T. In S_T there are K possible pathways, such that 1 ≤ K < ∞. Let $s_k \in S_T$ be a particular climate and non-climate pathway drawn from the distribution of possible pathways. The probability of s_k being realised is defined by the probability distribution function (pdf), p, such that:

$$\int_0^K p(s_k)\, ds_k = 1 \; and \; 0 < p(s_k) \leq 1 \; for \; all \; k.$$

a
(2)

These assumptions (2) ensure that all possible climate and non-climate pathways up to *period T* are included in the distribution. S_T and p may be deterministic or non-deterministic depending on the decision making context.

Each adaptation action accrues benefits and costs over the lead-time and lifetime from when the action is implemented (Ranger et al., 2010). The full benefits and costs accrued for an action depend upon the realised climate and non-climate pathway, and are defined in *present values* as follows:

$$B(a_j, s_k) = b_{jk}^c + b_{jk}^n \; , \tag{3}$$

Where:
b_{jk}^c = Benefits accrued for action a_j in pathway s_k that are related to climate drivers;
b_{jk}^n = Benefits accrued for action a_j in pathway s_k that are related to non-climate drivers; and,

$$C(a_j, s_k) = c_{jk}^c + c_{jk}^n \; , \tag{4}$$

Where:
c_{jk}^c = Costs accrued for action a_j in pathway s_k that are related to climate drivers; and,
c_{jk}^n = Costs accrued for action a_j in pathway s_k that are related to non-climate drivers.

The degree to which an adaptation action's benefits and costs relate to climate and non-climate drivers will depend on its type. System-wide actions are likely to have a higher proportion of benefits and costs associated with non-climate drivers than sector-specific actions, because they do not directly target specific climate drivers. Therefore, by identifying the non-climate benefits and costs, the decision maker can make more reliable comparisons between a_1 and alternative adaptation actions. Moreover, the classification of benefits and costs into climate and non-climate categories helps resolve the problem of additionality. By following this separation, the decision maker can identify how different objectives, such as sustainable development, are targeted by adaptation actions. This will help the decision maker understand if a_1 is targeting their preferred objectives (see section 2.3).

To further distinguish between system-wide or sector-specific actions, the framework categorises the benefits relating to climate drivers as follows:

$$b_{jk}^{c} = b_{jk}^{cd} + b_{jk}^{ci} , \tag{5}$$

Where:
b_{jk}^{cd} = *Benefits accrued for action* a_j *in pathway* s_k *that are directly related to climate drivers; and,*
b_{jk}^{ci} = *Benefits accrued for action* a_j *in pathway* s_k *that are indirectly related to climate drivers.*

The ratio of direct and indirect benefits relating to climate drivers depends upon the type of adaptation action. For system-wide actions:

$$\frac{b_{jk}^{cd}}{b_{jk}^{ci}} < 1 \ \ for\ any\ k, \tag{6}$$

And for sector-specific actions:

$$\frac{b_{jk}^{cd}}{b_{jk}^{ci}} > 1\ for\ any\ k. \tag{7}$$

Ratios (6) and (7) give the impression that adaptation actions can be definitively categorised, but this is not always the case. Adaptation actions that have a similar proportion of direct and indirect benefits relating to climate drivers may be difficult to categorise. For example, subsidising households to relocate to areas with a lower risk of flooding may appear to be a sector-specific action, as it directly reduces the households' vulnerability to flood risks (Bronen and Chapin, 2013). However, the subsidy may also provide a signal that causes the households to change their own behaviour in response to flood risks. For instance by planting crops that cope better with flooding. Therefore, the ratio of direct and indirect benefits will not always be clear enough to categorise the adaptation action as sector-specific or system-wide. However, the distinction between direct and indirect benefits is still useful, as it emphasises the need to identify indirect benefits. This is important in the case of system-wide actions, which predominantly incur benefits indirectly. Therefore, a_1 has more indirect than direct benefits in relation to its ability to reduce vulnerability to climate risks and exploit climatic opportunities. Section 2.2 looks at how the decision maker can identify these indirect benefits and make a more reliable comparison between a_1 and the alternative actions as a result.

2.2 Indirect Benefits of Building Adaptive Capacity

The next focus is on identifying the indirect benefits for the system-wide action in relation to climate drivers (b_{1k}^{ci}). One important consideration is how these actions change adaptive capacity (UKCIP, 2014). Adaptive capacity isn't sufficient for reducing vulnerability to climate risks and increasing opportunities to exploit climatic benefits. However, it is a necessary condition towards a system's ability to use resources for adaptation actions that can target climate drivers (Adger and Barnett, 2009; Burch, 2010; Tompkins et al. 2010). In this sense, system-wide actions that build adaptive capacity increase the quantity and/or quality of feasible adaptation actions that can themselves directly or indirectly target climate drivers. For example, early warning systems provide indirect benefits by improving the quantity and/or quality of adaptation actions that individuals can take in response to imminent climate risks. Therefore, system-wide actions may indirectly reduce vulnerability to climate risks and/or indirectly allow the exploitation of beneficial climatic opportunities. The indirect benefits that result are clarified by this framework.

Assume the decision maker evaluates changes in adaptive capacity up to *period t+1*. This period should capture the full change in adaptive capacity related to a_1, and it must fall somewhere between the decision period (*period t*) and the time horizon (*period T*). Let the process by which adaptive capacity in *period t+1* (A_{t+1}) is determined be defined as follows:

$$A_{t+1} = A_t + f\left(a_j^* \in A_t \;/\; b_{jk}^{cd} < b_{jk}^{ci}\right) + v_{t+1}\,, \qquad (8)$$

Where:
A_t = *Latent adaptive capacity in period t;*
$(a_j^* \in A_t \;/\; b_{jk}^{cd} < b_{jk}^{ci})$ = *Feasible system-wide actions implemented in period t; and,*
v_{t+1} = *Exogenous determinants of period t+1 adaptive capacity (realised between period t and t+1).*

Therefore, adaptive capacity follows a dynamic process that depends upon the both endogenous and exogenous factors (Armitage and Plummer, 2010; Brooks, 2003; Williamson et al., 2010). Endogenous factors are those controlled by the decision maker i.e. system-wide actions implemented by the decision maker. Exogenous factors are those not under the decision maker's control e.g. natural disasters that damage adaptive capacity. The function f captures the process by which implemented system-wide actions change adaptive capacity. If system-wide actions build adaptive capacity then this function is increasing, such that:

$$A'_{t+1}(a_j^* \in A_t \;/\; b_{jk}^{cd} < b_{jk}^{ci}) > 0\,. \qquad (9)$$

However, it is recognised that not all system-wide actions will increase adaptive capacity. Some actions may purposefully decrease adaptive capacity. Similarly, if the determinants of adaptive capacity are not fully understood, actions that are expected to build adaptive capacity may unintentionally decrease adaptive capacity (Adger and Vincent, 2005). For simplicity, the framework assumes a_1 builds adaptive capacity in line with equation (9).

To identify the indirect benefits associated with a_1, the potential future benefits and costs from adaptation actions it facilitates need to be evaluated. Identifying the new and/or improved adaptation actions facilitated by a_1 is synonymous with identifying the change in adaptive capacity caused by a_1, which is defined as follows:

$$\Delta A^{a_1} = (A_{t+1} - A_t)^{a_1}. \tag{10}$$

In equation (10), the impact of exogenous variables and other system-wide actions on adaptive capacity is controlled for. These influences must be controlled for in order to isolate the impact of a_1 on adaptive capacity. Assuming a_1 is the only system-wide action implemented in *period t*, Figure 3 demonstrates the separation of these two effects.

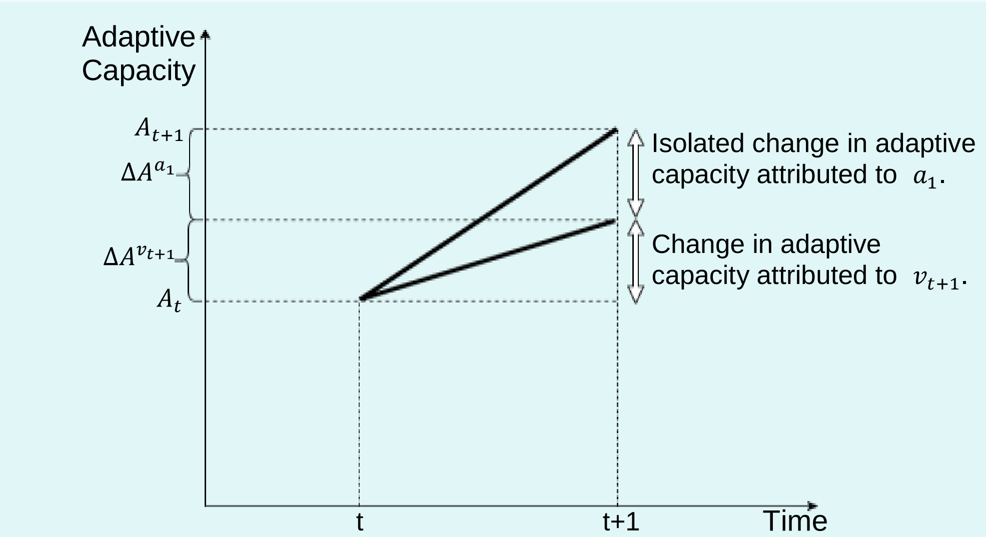


Figure 3: Change in adaptive capacity between *period t* and *period t+1*. The change in adaptive capacity is attributed to endogenous factors (a_1) and exogenous factors (v_{t+1}).

In Figure 3, the gross change in adaptive capacity between *period t* and *period t+1* is equal to the sum of the change caused by exogenous factors ($\Delta A^{v_{t+1}}$) and the change caused by a_1 (ΔA^{a_1}). The decision maker must separate these two effects in order to isolate the impact of a_1 on adaptive capacity. Therefore, they must understand how both a_1 and exogenous factors will influence adaptive capacity between *period t* and *period t+1*. In reality, multiple system-wide actions may be implemented in *period t*. In this case, the decision maker must still attempt to isolate the impact of a_1 on adaptive capacity, so that the benefits of the actions facilitated by a_1 can be indirectly attributed to it.

However, assigning values to changes in adaptive capacity is difficult (see section 4.1). Therefore, this framework proposes that the new and/or improved adaptation actions facilitated by a_1 signify these changes in adaptive capacity. As a result, the decision maker needs to identify the set of new and/or improved adaptation actions facilitated by a_1, which is defined as follows:

$$\Delta A^{a_1} = \{a_1^{a_1}, \dots, a_l^{a_1}\}, \tag{11}$$

Where:
There are $L > 0$ *feasible adaptation actions facilitated by* a_1*;*
$A_t \cap \Delta A^{a_1} = \emptyset$; and,
$a_l^{a_1} \in \Delta A^{a_1}$ *is a feasible adaptation action facilitated by* a_1*.*

For a given facilitated action, $a_l^{a_1}$, the benefits and costs take the same form as those defined in the general framework. Therefore, each facilitated action has benefits and costs relating to climate and non-climate drivers. In addition, the ratio of benefits directly and indirectly related to climate drivers will largely depend on whether it is a sector-specific or system-wide action. As a result, the value chain attributed to the original system-wide action (a_1) will depend upon the type of adaptation actions it facilitates. Figure 4 highlights the increasing complexity of identifying adaptation actions that may have originally been facilitated by a_1.

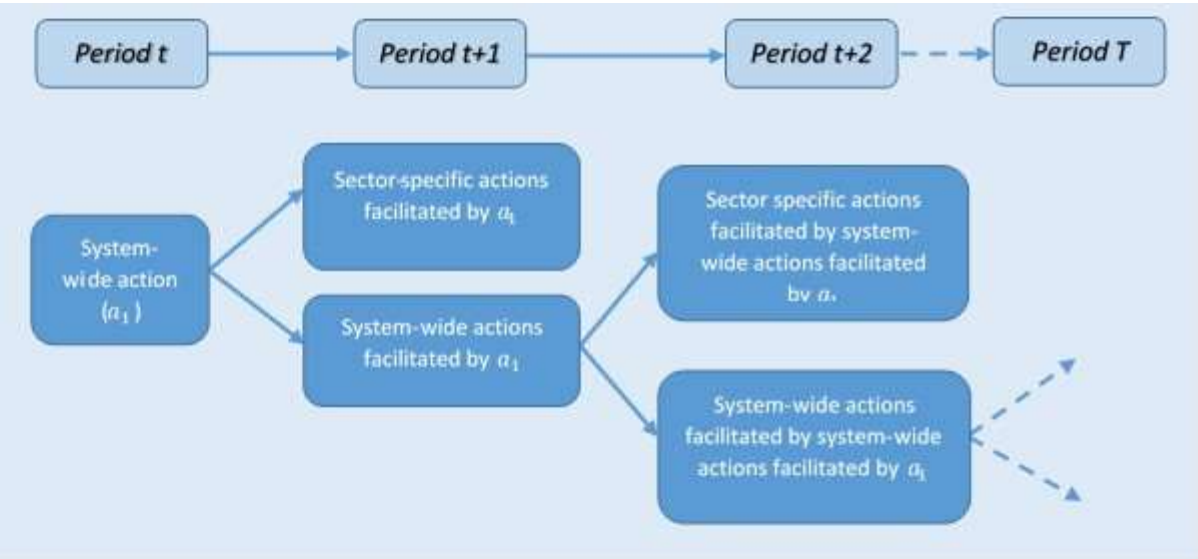


Figure 4: Adaptation actions facilitated by the system-wide adaptation action, a_1. *Period t+1* actions are the first order of adaptation actions directly facilitated by a_1.

For simplicity, the framework focuses on the first order of adaptation actions facilitated by a_1 (ΔA^{a1}). From Figure 4, these are the actions directly facilitated by a_1 in *period t+1.* To attribute the value of these actions to a_1, their net present values need to be evaluated and aggregated, such that:

$$b_{1k}^{ci} = \sum_{l=0}^{L}\left[B\left(a_l^{a_1}, s_k\right) - C\left(a_l^{a_1}, s_k\right)\right] \tag{12}$$

Therefore, in a given pathway the indirect benefits attributed to a_1 are the sum of the net present values of all the adaptation actions directly facilitated by a_1. It is recognised that b_{1k}^{ci} will also capture non-climate benefits and costs associated with the facilitated actions. However, given that the primary aim of a_1 is to target climate drivers, the total value of the actions facilitated by a_1 is captured here. These indirect benefits must be considered in conjunction with all the other benefit and cost categories defined in the general framework. This will allow for a more accurate evaluation of system-wide actions. Consequently, the value of system-wide actions can be more reliably compared to that of sector-specific actions. This will reduce the chance of misallocating resources when deciding between the alternative actions.

2.3 Decision Phase

The decision maker must now determine which adaptation actions to implement based on the evaluation of their benefits and costs. There are a number of decision paradigms that need to be considered, which depend upon the quantity and quality of information the decision maker has, and the beliefs and preferences of the decision maker. This framework categorises the decision contexts into those of risk and those of uncertainty. Decision making under risk deals with situations when the decision maker has probabilistic information. Decision making under uncertainty covers situations where probabilistic information is unreliable or unavailable (MEDIATION, 2013; Ranger et al., 2010; Willows and Connell, 2003). The structure of this section follows Annex A of Ranger et al.'s (2010) UK Policy Brief; objective criteria are developed first, before introducing normative criteria and more complex paradigms.

2.3.a Decision Making Under Risk

First consider an entirely objective decision context, where the decision maker knows all the parameters defined in the conceptual framework. In this case, feasible adaptation actions should only be considered if they are expected to have a positive net present value. Within this set, the decision maker should rank the alternatives using their expected net present values and implement the actions with the highest values. Therefore, a_1 should only be implemented if it satisfies the following criterion:

$$\{a_j^* \in A_t\} = argmax\left\{\sum_{a_j^*=0}^{J}\int_0^K \left[B(a_j,s_k) - C(a_j,s_k)\right] dp(s_k)\right\} \quad (13)$$

The quantity and/or quality of actions within the set of implemented actions $\{a_j^* \in A_t\}$ is constrained by adaptive capacity (A_t) in *period t*. There may be one or multiple actions within the set of implemented actions. In any case, the expected net present value of a_1 would need to be sufficiently high in order to be implemented by the decision maker. If the benefits and costs can be monetised, the criterion defined in equation (13) requires the decision maker to carry out expected benefit-cost analysis (Boardman et al., 2011).

Having defined an objective criterion for choosing adaptation actions, the framework now considers normative aspects. The decision maker's preferences over outcomes and attitudes towards risk are defined by a utility function[1]. For a given adaptation action and pathway, the utility function is defined as follows:

$$U(a_j,s_k) = u[B(a_j,s_k) - C(a_j,s_k)] \quad (14)$$

The functional form of the utility function is undefined. This allows the framework to be applied to any plausible decision context. In the case of public choice, utility is synonymous with social welfare. This requires the decision maker to be the "perfect agent", such that their preferences accurately reflect social preferences i.e. they act in the best interest of the public. For this, efficient preference elicitation and aggregation needs to take place. It also requires the

[1] See Stigler (1950) for a two part review of the origins of utility theory in economics. For prominent axiomatic derivations refer to von Neumann and Morgenstern (1944) and Savage (1954).

decision maker to have no conflicting objectives to that of the public. Whilst these assumptions are unrealistic (Arrow, 1963), they allow the framework to generalise for problems facing both private and public decision makers.

In normative contexts, the framework assumes that the decision maker wants to maximise discounted expected utility. Therefore, the combination of adaptation actions that maximise discounted expected utility should be implemented. In general, a_1 should only be chosen if it falls within the set of actions that satisfy the following decision criterion:

$$\{a_j^* \in A_t\} = argmax\left[\sum_{a_j^*=0}^{J} \int_0^K U(a_j, s_k)\, dp(s_k)\right] \tag{15}$$

Whilst equation (15) appears to be similar to equation (13), the inclusion of the decision maker's utility function in equation (15) may cause significant differences in the adaptation actions implemented by the decision maker (Ranger et al. 2011). For example, if there is a choice between two adaptation actions with the same expected net present value, a risk averse decision maker will prefer the action with the lower variance of net present values. Therefore, when the decision maker knows all the parameters defined in the conceptual framework, classic expected utility theory is used to define the decision criterion. This provides an optimal decision framework comparable to those used in neoclassical economics e.g. von Neumann and Morgensterns' (1944) expected utility theory.

With the introduction of utility, there is likely to be an optimal level of adaptation that maximises the decision maker's discounted expected utility. This optimal level of adaptation will depend on the competing resource uses, the decision maker's risk appetite and how effective the resources are at reducing vulnerability to climate risks. In terms of competition, objectives such as mitigation and sustainable development may compete for adaptation resources. However, it is increasingly recognised that these objectives may be complimentary to adaptation (IPCC, 2014a-f). For the decision maker's risk preferences, Klinke and Renn (2002, 2013) define acceptable, tolerable and intolerable levels of risk. They suggests that optimal levels of adaptation will prioritise reductions in vulnerability to intolerable risks. Adaptive capacity determines how effective the available resources are at reducing vulnerability to intolerable climate risks and exploiting climatic opportunities through adaptation actions. Therefore, preferences and competing objectives can place further constraints on the implementation of adaptation actions. The resulting first-order conditions for utility maximisation state that the decision maker should implement adaptation actions so that their expected marginal gain from another unit of adaptation equals the cost.

2.3.b Decision Making Under Uncertainty

Up until this point, the framework has assumed the decision maker knows a number of different parameters with certainty. These parameters include:

- The set of feasible adaptation actions (A_t);
- The set of possible climate and non-climate pathways, (S_T);
- The pdf of these pathways, (p);
- The benefits and costs of an adaptation action in each pathway [$B(a_j, s_k)$ and $C(a_j, s_k)$]; and,
- The processes by which adaptive capacity changes.

These may be simplistic assumptions, but they allow the framework to demonstrate the problem with identifying the full benefits and costs associated with system-wide and sector-specific actions. We shall now consider the implications of relaxing the climate and non-climate pathway assumptions.

Suppose the decision maker knows the set of possible climate and non-climate pathways (S_T), but is not able to determine the true pdf for these pathways (p). Therefore, the decision maker uses all the information available to them to estimate the likelihood of each pathway being realised. Their beliefs are captured by the subjective pdf p^e, such that:

$$\int_0^K p^e(s_k)\, ds_k = 1 \; and \; 0 \leq p^e(s_k) \leq 1 \; for \; all \; k. \qquad \text{a (16)}$$

The decision maker may therefore believe that a particular pathway will not occur $[p^e(s_k) = 0]$. However, the decision maker must at the very least believe one pathway will occur with certainty in order to have a complete set of beliefs in the probability space. It is arguable that in the majority of contexts, the decision maker has at least some information about the likelihood of the future climate and non-climate pathways from their own experience (Millner and Washington, 2011). This information is used to form these beliefs and define the subjective pdf. The condition for maximising discounted expected utility will now depend upon the subjective rather than the objective pdf, such that:

$$\{a_j^* \in A_t\} = argmax \left[\sum_{a_j^*=0}^{J} \int_0^K U(a_j, s_k)\, dp^e(s_k) \right] \qquad \text{a (17)}$$

Equation (17) now adopts the form of discounted subjective expected utility maximisation (Savage 1954). The subjective beliefs may change the decision maker's expectations about the future climate and non-climate pathways compared to those in equation (15), as the subjective and objective pdf's do not necessarily coincide, i.e. $p^e \neq p$. This change in expectations might alter the set of adaptation actions that maximise expected utility. In this case maladaptation might occur, because the alternatives implemented do not reflect the true probabilities of the future climate and non-climate pathways. This is a problem of adverse selection, which is likely to be exacerbated in decision making contexts with longer time horizons. However, the decision maker may be aware of this. In such cases, they may delay making decisions until they have better information or use criteria that do not require probabilistic information (see section 2.3.c)

2.3.c Decision Making Under Deep Uncertainty

So far the framework has used optimisation procedures to test whether the system-wide action (a_1) maximises discounted expected utility. These approaches are dependent on at least some probabilistic information being available to the decision maker about the likelihood of the future climate and non-climate pathways. However, it is possible that the decision maker has no probabilistic information. Similarly, if the decision maker has probabilistic information, they may perceive that it is unreliable and therefore choose not to use it (Millner and Washington, 2011). These decision making contexts are underpinned by deep uncertainty, and are particularly relevant for adaptation actions whose benefits and costs accrue over long time horizons (Hallegatte et al., 2011, 2012).

In situations of deep uncertainty, it is recommended that the decision making criteria shifts from choosing optimal adaptation actions, to choosing ones that are robust and flexible in order to avoid maladaptation (MEDIATION, 2013; Ranger et al., 2010; Willows and Connell, 2003). Robust and flexible criteria favour adaptation actions that perform satisfactorily across a number of possible future pathways. For example, the decision maker may choose to implement the set of adaptation actions that maximise their average discounted utility across the possible future climate and non-climate pathways:

$$\{a_j^* \in A_t\} = argmax\left\{\sum_{a_j^*=0}^{J} \frac{\sum_{k=0}^{K}[U(a_j, s_k)]}{K}\right\} \quad \text{a (18)}$$

Criterion (18) does not use probabilistic information, and can therefore be used in situations of deep uncertainty. Examples of other decision criteria that do not use probabilistic information can be found in Annex 1. From (18), the decision maker should only implement a_1 if it falls within the set of adaptation actions that maximise the average discounted utility across the possible future pathways. If a_1 satisfies this criterion it is said to be robust.

Certain types of adaptation actions may be more robust than others. For example, flexible and incremental adaptation actions that can be altered once more information becomes available are likely to be robust (Leary, 1999). Similarly, “soft” behavioural actions may be more robust than “hard” infrastructural actions, as they build adaptive capacity and avoid irreversible investments (Frankhauser and Burton, 2011). In addition, the literature on quasi-option values also suggests that adaptation actions that preserve and increase future adaptive capacity may be suitable for situations of deep uncertainty, as they allow decision makers to wait for information to improve before committing to more permanent actions (Hallegatte, 2009). Therefore, if a_1 has these qualities it is likely to be preferred to alternative adaptation actions in situations of deep uncertainty.

As in section 2.3.a, the decision maker’s preferences and competing objectives will determine which adaptation actions are actually chosen. For example, the decision maker may be extremely risk averse and use the Minimax decision criterion to choose the adaptation action or strategy that provides the lowest value of the maximum discounted utility in any future pathway. In addition, if the decision maker has multiple objectives then a multiple criteria approach may be more suitable to evaluate the alternatives. Therefore, the decision maker’s preferences and objectives will still determine which adaptation actions are ultimately chosen in decision making contexts of deep uncertainty.

3 Application: Developing New Climate Change Scenarios

In this application, an investment into the development of new climate change scenarios is evaluated. It focuses on how the value of developing new scenarios may be indirectly realised, through their influence on adaptive capacity. This will demonstrate how the conceptual framework can be applied to a feasible system-wide action. The impact of the new scenarios on the decision maker's available information is also assessed in section 3.2.

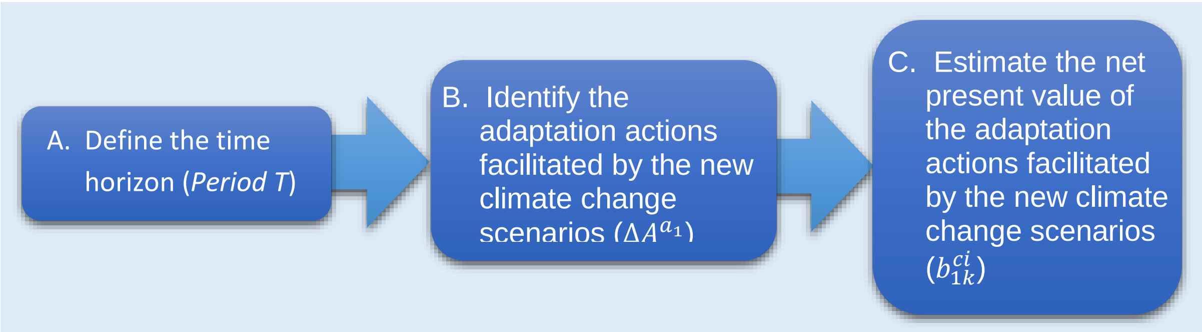
3.1 Main Application

Consider the following setting. Current climate change scenarios are only reliable at national level. A decision maker is deliberating an investment into developing new climate change scenarios, which will improve the granularity to subnational level. This will give the decision maker higher resolution information about specific locations of flood risks in a river basin. Following this, they can build appropriate flood defences to protect the areas at risk. For simplicity, assume the future climate and non-climate pathway is deterministic, and that the future climate pathway will have high average rainfall. The areas at risk of flooding as a result of this rainfall are known with certainty once the new scenarios have been developed. Consequently, there is no risk or uncertainty in the decision phase after the new scenarios have been developed.

The conceptual framework is now applied to this setting. Developing new climate change scenarios is assumed to be a feasible adaptation action (a_1) as determined by the current adaptive capacity (A_t). It therefore uses resources that have competing uses (a_{J-1}). Accordingly, there are trade-offs associated with investing in the development of the new scenarios. This justifies the need to evaluate the benefits and costs.

Developing new climate change scenarios is classified as a system-wide action. From the conceptual framework, this means the benefits from this investment are predominantly indirect with respect to climate drivers ($b_{1k}^{ci} > b_{1k}^{cd}$). This is intuitive as the new scenarios do not target specific flood risks by themselves. However, they provide the decision maker with information about the locations of the flood risks and the need for actions in response to these risks. This change in the quantity and/or quality of actions that a decision maker can take is modelled by the change in adaptive capacity that results from developing the new scenarios. Therefore, to identify the indirect benefits the decision maker follows the process in Figure 5.

Figure 5: Process for identifying the indirect benefits associated with the new climate change scenarios (a_1).



A. Define the Time Horizon:

The time horizon needs to be long enough to capture the full benefits and costs related to developing the new climate change scenarios. This reduces the possibility of misallocating resources. However, it is recognised that longer time periods are accompanied by greater uncertainty. Therefore, the time horizon should be short enough to reliably attribute the benefits and costs to the investment of developing new scenarios. This is in line with HM Treasury's (2015) Green Book for public policy and project appraisal.

One key uncertainty is the lifespan of the actions that new climate change scenarios facilitate. Given that it is difficult to measure this, the application assumes the decision maker has perfect information about the lifespans of the actions facilitated by the new scenarios. In this context, the new scenarios only facilitate the implementation of flood defences. Therefore the time horizon also needs to capture the benefits and costs associated with the flood defences. A time horizon in excess of thirty or fifty years would not be unreasonable, given the expected lifespan of flood defences such as the Thames Barrier (Environment Agency, 2012).

Assume the new scenarios will be fully developed after two years and accrue no direct benefits and costs thereafter. The change in adaptive capacity will be measured over these two years, to capture the impact of the fully developed new scenarios. The flood defences are then implemented immediately using these scenarios and are completed in three years. The defences are expected to last for twenty-five years. Therefore, the time horizon is thirty years[2]. Using HM Treasury's (2015) proposals, an annual discount rate of 3.5% is applied to the benefits and costs that are incurred at the end of each year over the thirty year period.

B. Identify the adaptation actions facilitated by the new climate change scenarios:

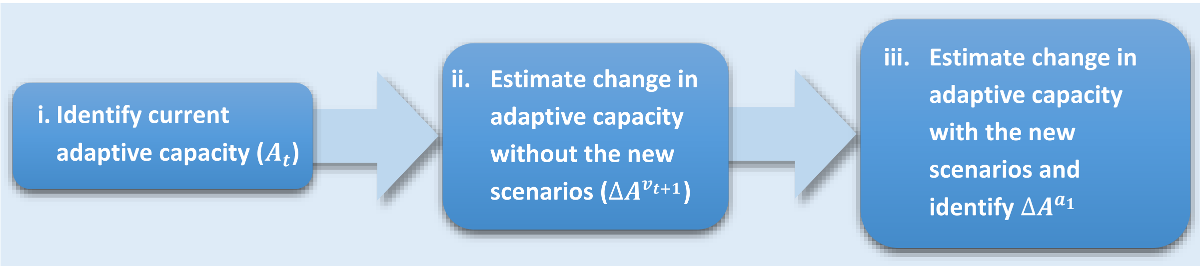


Figure 6: Process for identifying changes in adaptive capacity related to the new climate change scenarios (a_1). The unit of analysis for adaptive capacity is the set of feasible adaptation actions.

In the previous step, the decision maker decided to measure the change in adaptive capacity over the two years it will take for the new climate change scenarios to be fully developed. Therefore, they should follow the three sub-steps outlined in Figure 6 to estimate the change in adaptive capacity and identify the adaptation actions facilitated by the new scenarios.

[2] This time horizon was arbitrarily chosen to allow for a simple discount rate. Refer to the HM Treasury's (2015) Green Book for guidance on discounting projects or policies with longer time horizons.

Adaptive capacity is defined in the conceptual framework as the set of feasible adaptation actions. Suppose current adaptive capacity is represented by 100 feasible adaptation actions **(i)**. Two years from now, the set of feasible adaptation actions will increase to 120 without the development of new climate change scenarios **(ii)**. However, with the development of new scenarios 121 adaptation actions will be feasible in two years. Therefore, the development of new scenarios facilitates one extra adaptation action, such that $\Delta A^{a_1} = a_1^{a_1}$ **(iii)**. $a_1^{a_1}$ is the sector-specific action of building flood defences for the areas known to be at risk of flooding, which is facilitated by the new scenarios. It is likely that the new scenarios will facilitate more than one adaptation action in the future. In this setting, the action of building flood defences could therefore be symbolic of multiple facilitated adaptation actions. At this point, the time horizon chosen in step A may need to be revised to allow for the full benefits and costs of any facilitated adaptation actions to be attributed to the development of the new scenarios.

This application doesn't account for any uncertainty about how adaptive capacity is expected to change. However, uncertainty could be incorporated by conjecturing multiple states of future adaptive capacity, and then assessing the impact of the new scenarios in each of these states. Another criticism may be the abstract nature of bottom-up approach to measuring adaptive capacity i.e. the quality and/or quantity of adaptation actions. However, this approach allows the problem to be defined and provides a clear process for assigning values to changes in adaptive capacity.

C. Estimate the net present value of the facilitated adaptation actions:

To value the indirect benefits, the net present value of the flood defences facilitated by the new climate change scenarios needs to be calculated. The future values of the flood defences are arbitrarily represented in Table 2.

Table 2: Future values of flood defence benefits and costs in the high average rainfall pathway, including the dates they are incurred.

Flood Defences' Benefits and Costs	Amount (£/annual)	Dates Incurred (Year End)
Fixed Costs for Implementation	£30m	Years 3 to 5
Maintenance Costs	£5m	Years 6 to 30
Benefits from Protection Against Flood Risks	£15m	Years 6 to 30

Using the future values in Table 2 and the annual discount rate of 3.5%, the present value of the total cost is £147.85m[3]. The present value of the benefits from the protection against flood risks exceeds the present value of the costs, at £208.15m. Therefore, the flood defences have a positive net present value of £60.31m and should be built if a positive net present value criterion is used. However, the flood defences were facilitated by the development of new

[3] See Annex 2, Tables a and b, for the present value calculations of the flood defences' benefits and costs.

climate change scenarios, which allowed the decision maker to take action to protect the areas known to be at risk of flooding. Therefore, the net present value calculated here is attributed to the development of the new scenarios, such that b_{1k}^{ci} = £60.31m.

This value needs to be combined with the other benefits and costs defined in the conceptual framework. Assume the cost of developing the new climate change scenarios is £3m each year for two years until they are fully developed, such that $C(a_1)$ = £5.70m[4]. As previously discussed, the benefits of the new scenarios in terms of directly targeting climate drivers are likely to be negligible. Assume they are zero for simplicity, such that b_{1k}^{cd} = 0. However, the new scenarios are likely to have co-benefits with non-climate objectives (IPCC, 2014a-f). For example, the reduction in uncertainty about the location of flood risks that the new scenarios bring could boost business confidence and stimulate economic growth (Asteriou and Price, 2005; Dixit and Pindyck, 1994). These co-benefits are difficult to quantify, but assume for simplicity that they are less than the present value of the total costs, such that $b_{1k}^{n} < C(a_1)$ = £5.70m.

Therefore, without accounting for the value of the flood defences facilitated by the new climate change scenarios, the net present value of developing new climate change scenarios would be negative. From an objective standpoint the new scenarios would not be developed, and the current scenarios available would not help flood defences definitively protect at risk areas. Therefore, maladaptation might occur if the cost of not building the flood defences or building them in the wrong place outweighs the cost of building them in the right place, courtesy of the new scenarios (IPCC, 2014b). However, with the inclusion of the indirect benefits, the total benefits related to climate drivers ($b_{1k}^{c} = b_{1k}^{cd} + b_{1k}^{ci}$ = £60.31m) are significant enough to make the development of new climate change scenarios an attractive investment using the positive net present value criterion. If developed, the new scenarios would inform the decision maker about where to build the flood defences to protect the areas at risk of flooding. Therefore, by identifying the indirect benefits associated with the new scenarios, the decision maker can make more accurate comparisons between developing the new scenarios and alternative adaptation actions.

In normative terms, the decision depends upon the set of alternative actions and the decision maker's utility function. In this setting, the outcomes are deterministic and therefore expectations and risk are removed. Therefore, if the net present value of the new scenarios maximise utility, then the decision maker should invest in their development. Likewise, if resources are sufficient to implement several adaptation actions, then the new scenarios should only be developed if they are part of the combination of actions that maximise utility (see equation 15). To make these comparisons, the utility attained by the new scenarios needs to be benchmarked against alternative adaptation actions or inactions. The optimal level of adaptation for the decision maker will depend upon their preferences towards adaptation and other objectives (IPCC, 2014d), and whether they perceive the flood risks to be intolerable or not (Klinke and Renn, 2002, 2013).

This application highlights the importance of identifying the indirect benefits of system-wide adaptation actions. The adaptive capacity they build facilitates new and/or improved adaptation actions that can directly and indirectly target to climate drivers. Including these indirect benefits increases the opportunity cost of not choosing system-wide actions. This will increase the appeal of system-wide actions relative to other adaptation actions in the decision making process.

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[4] This is the present value of the total costs, calculated using the annual discount rate of 3.5% over the 2 years it takes to develop the new climate change scenarios.

However, the decision making context in this section is unrealistic. The application explicitly assumes the decision maker knows:

- The climate and non-climate pathway with certainty;
- The areas at risk of flooding with certainty as a result of the new climate change scenarios;
- The time over which all relevant benefits and costs are incurred; and,
- The change in adaptive capacity with certainty.

These are simplistic assumptions, but they clarify the process of identifying the indirect benefits of system-wide actions. In addition, the application implicitly assumes the economic benefits and costs can be monetized. Both market and nonmarket valuation techniques[5] may be used to achieve this. However the benefits and costs need careful consideration to make sure they are fully captured. In the extension of this application, some of the explicit assumptions are relaxed.

3.2 Extension: Introducing Risk and Uncertainty

Consider the same setting as in section 3.1. However, the new climate change scenarios now provide probabilistic rather than locational information. As a result, risk and uncertainty are introduced by defining probabilistic future climate pathways. There are two pathways: the high average rainfall pathway and a new low average rainfall pathway. These pathways are realised after the flood defence investment decision has taken place. Therefore, only the benefits associated with the flood defences are directly affected. The change in adaptive capacity resulting from the new scenarios is still assumed to be deterministic.

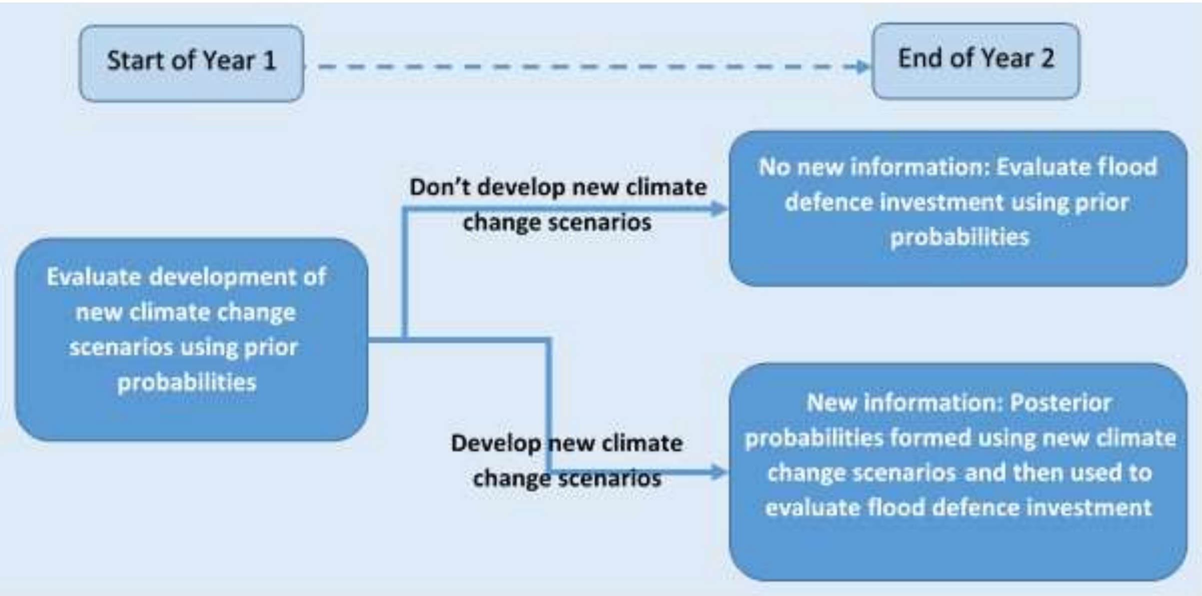

Figure 7: Process for evaluating the development of new climate change scenarios and the flood defence investment. The probabilities used in the evaluation of the flood defences are contingent on whether the new climate change scenarios are developed or not.

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[5] For a review of appropriate nonmarket valuation techniques refer to Pearce (2002).

Figure 7 defines the evaluation process undertaken by the decision maker. Before deciding whether to develop the new climate change scenarios, the decision maker forms subjective beliefs about the likelihood of each pathway being realised (p^e). These prior probabilities are formed using the current climate change scenarios. The prior probabilities are then used to evaluate the development of the new scenarios. If the new scenarios are developed, the decision maker updates their probabilistic beliefs using the new information the scenarios provide. These posterior probabilities (p) are then used to evaluate the flood defence investment. However, if the new scenarios aren't developed the prior probabilities are used to evaluate the flood defence investment. Therefore, the flood defence investment is contingent on whether or not the new climate change scenarios are developed.

At the start of Year 1, assume the decision maker believes the high average rainfall pathway will occur with probability 0.3 and the low average rainfall pathway with probability 0.7. The discounted total costs and non-climate related benefits of the new climate change scenarios are the same as before, such that $C(a_1)$ = £5.70m and $b_{1k}^{n} < C(a_1)$ = £5.70m. Similarly, the benefits directly related to climate drivers are zero like before, such that $b_{1k}^{cd} = 0$. Therefore, without accounting for the indirect benefits of the flood defences, the new scenarios are not considered a worthwhile investment in net present value terms.

The indirect benefits related to the flood defences now need to incorporate the probabilistic information. Assume the discounted total costs for the flood defence investment do not depend on the realised pathway and are the same as before at £147.85m. The future value of benefits for the flood defence investment in the high average rainfall pathway are the same as before (£15m). However, the future value of the benefits in the low average rainfall pathway are less than in the high average rainfall pathway, at £6m each year from years 6 to 30. The discounted benefits in the low average rainfall pathway total £83.26m[6]. Therefore, the net present value of the flood defences in the low average rainfall pathway is -£64.58m. Using the prior probabilities (p^e), the expected net present value of the flood defences is -£27.12m[7]. Therefore, without the development of the scenarios the flood defences do not appear to be an attractive investment using the positive expected net present value criterion.

However, with the development of the new climate change scenarios comes improved information about the likelihood of each climate pathway. Assume the new scenarios provide the decision maker with the true probability distribution (p), which states that the high average rainfall pathway will occur with probability 0.6 and the low average rainfall pathway with probability 0.4. If the decision maker had this information at the start of year 1, their evaluation of the flood defences would calculate an expected net present value of £10.35m[8]. Therefore, with the development of the new scenarios, the flood defences are considered a worthwhile investment using the positive net present value criterion. In this sense, the flood defences are facilitated by the new climate change scenarios, because the new probabilistic information provided by the new scenarios ensures the positive expected value criterion is satisfied.

It should be recognised that the original expected net present value (-£27.12m) is based on misinformation; the prior probabilities do not coincide with the true probabilities of the two climate pathways. With the new climate change scenarios, the posterior probabilities reflect

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[6] See Annex 1, Table a, for the present value calculations of the flood defence benefits in each pathway.

[7] See Annex 1, Table c, for the expected net present value calculations using the prior probabilities.

[8] See Annex 1, Table d, for the expected net present value calculations using the posterior probabilities.

the true probabilities and the expected net present value of the flood defences is £10.35m. Without the development of the new scenarios, this expected value isn't attained. Therefore, the indirect benefits of the new scenarios is equal to the £10.35m value of the flood defences it facilitates. With the inclusion of this indirect value (b_{1k}^{ci}), the new scenarios now appear to be an attractive investment:

$$\pounds 10.35m + b_{1k}^{cd} + b_{1k}^{n} - C(a_1) > \pounds 4.65m$$

However, this evaluation is based on the posterior probabilities, which are unknown to the decision maker before the development of the new climate change scenarios. Using the prior probabilities, the decision maker would not invest in the development of the new scenarios, which in turn will lead them to not build the flood defences. Given the true probability distribution of the climate pathways, this would lead to maladaptation; the lack of flood defences would not reflect the true probability of flood risks.

In this setting, the informational value the new climate change scenarios provide needs to be accounted for. This requires the decision maker to be aware of the limitations of their current information. If they recognise the potential for the new scenarios to improve future adaptation investment decisions, then the value attributed to the development of the new scenarios will increase. The perceived value of climate information has been modelled by Millner and Washington (2011). They argue that the value and uptake of climate forecasts depends on their perceived accuracy, among other factors. Therefore, whether or not the decision maker uses the current and new scenarios to form their beliefs depends on how accurate they perceive them to be.

It may be that the decision maker believes the current climate change scenarios are so unreliable that they choose not to use them. In such cases, the decision maker is unable to form probabilistic beliefs about the climate pathways. As a result, robust rather than optimal decision procedures should be used to evaluate the adaptation actions. Robust procedures sacrifice the performance of optimisation procedures in order to achieve satisfactory outcomes (Ranger et al. 2010). Therefore, developing new scenarios may be a worthwhile investment, if it increases the uptake of this information and informs the decision maker's beliefs about the likelihood of the future climate pathways. However, Hallegatte (2009) and Hallegate et al. (2011, 2012) argue that reliable decadal climate predictions won't be achieved without significant investments. Therefore, the investment into the development of new climate change scenarios would need to be significant enough to ensure their reliability. Otherwise, decision makers may still choose to neglect the information the scenarios provide, and instead use robust procedures to decide between alternative adaptation actions.

Regardless of which decision procedures the decision maker chooses to use, the new climate change scenarios have an indirect value that needs to be accounted for. They provide the decision maker with better information about the likelihood of each future climate pathway, and therefore allow them to make a better quality decision about whether to build flood defences or not. By accounting for this informational value, the decision maker can make more reliable comparisons between the development of the new climate change scenarios and alternative adaptation actions. If this value is not accounted for, then the new scenarios may not be developed and inappropriate flood defences may be built. This case of maladaptation favours the development of the new scenarios.

As with the main application, the decision making context will determine whether the decision maker actually decides to invest in the both the new climate change scenarios and the flood defences. For example, the decision maker's level of risk aversion may be such that they invest in the new flood defences even without the new scenarios. In contrast, their risk preferences may perceive the flood risks to be tolerable even with the development of the new scenarios (Klinke and Renn 2002, 2013). The optimal level of adaptation will depend upon these factors, and is also constrained by competing objectives and resource uses (IPCCC, 2014c).

This extension provides useful insights into how risk and uncertainty affect the adaptation decision making process. System-wide actions that improve future adaptation decisions may be considered to be worthwhile investments in some instances. The development of new climate change scenarios may well fall into this category. It is recognised that both the main application and its extension are contrived. However, the example was developed for demonstrative purposes only, and is not anticipated to be truly reflective of all decisions and contexts.

4 Practical Considerations: Evaluating System-wide Actions

This section handles practical considerations for the application of the conceptual framework to realistic decision making contexts. Some of these issues have already been introduced. For example, decision criteria were introduced in section 2, and section 3 covered the application of the framework in two specific contexts. Similarly, a logical process for evaluating the development of new climate change scenarios was suggested in section 3 (Figures 5 and 6). Following on from this, the full process for evaluating any system-wide action relative to alternative adaptation actions is defined in Figure 8. This is an applied version of Ranger et al.'s (2010) decision making process.

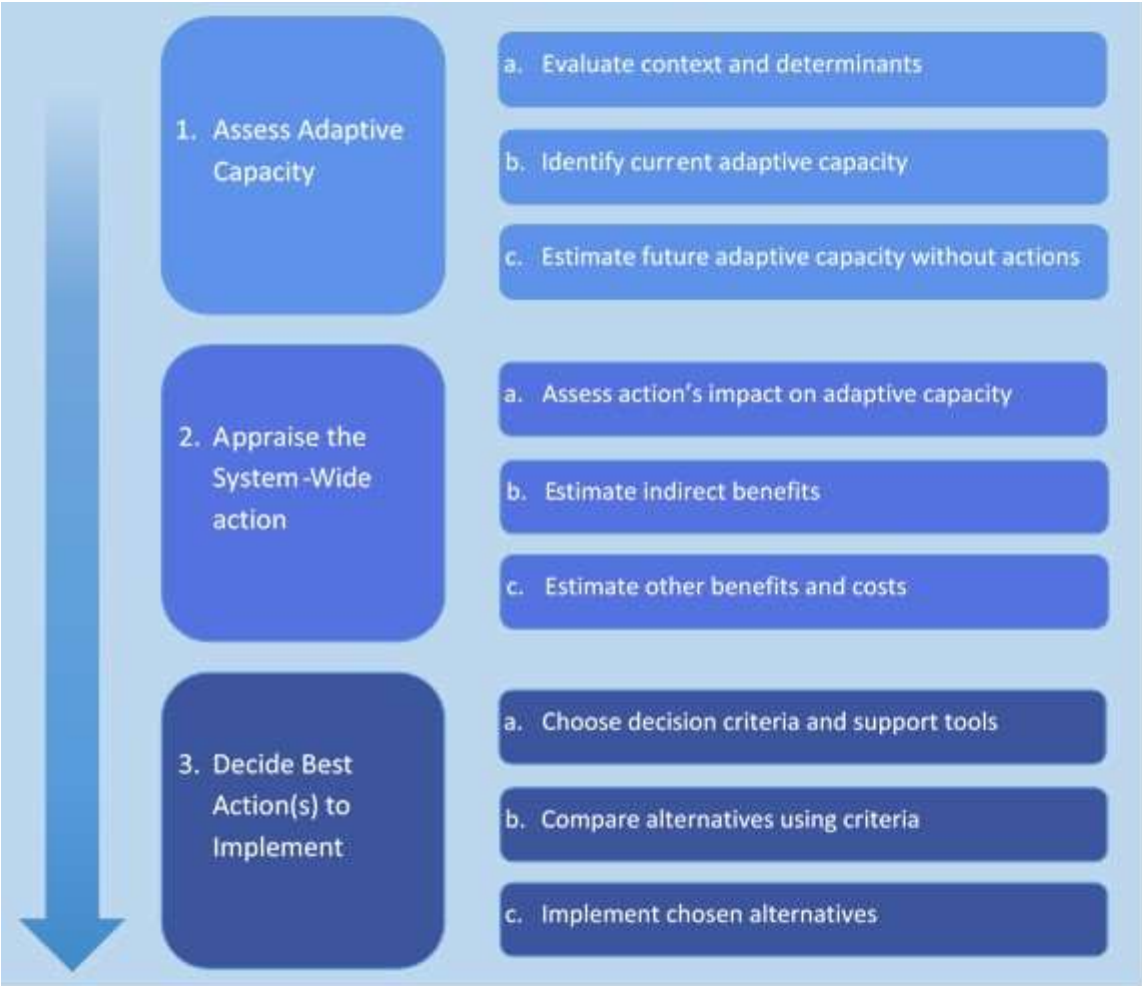

Figure 8: Three step process for evaluating a system-wide action relative to alternative adaptation actions.

In each step of the process in Figure 8, the conceptual framework faces practical limitations. For assessing adaptive capacity (1), the state-of-the-art techniques used are not immediately relevant to this framework. For appraising system-wide actions (2), uncertainty and the techniques used to value the benefits and costs may make appraisals more complicated. Finally, for deciding which action(s) are best to implement (3), the decision criteria and support tools are very context specific and need careful consideration. Therefore, the decision maker must be aware of these practical limitations when trying to follow this process. This section deals with some of these concerns.

4.1 Assessing Adaptive Capacity

Adaptive capacity must be assessed in order to determine how the system-wide action might affect it. Therefore, the resources and constraints of current adaptive capacity need to be evaluated (IPCC, 2014e). In addition, the processes by which adaptive capacity is determined need to be understood (Adger and Vincent, 2005). This will help the decision maker understand how their actions influence adaptive capacity, and in turn how they can target climate drivers. However, adaptive capacity is not an observable variable. As a result, proxies for adaptive capacity and climate risk vulnerability have traditionally been developed. However, these indices measure the outcomes of adaptive capacity in terms of vulnerabilities, and not adaptive capacity itself. Therefore, there are some limitations in using indices for the assessment of adaptive capacity in this framework.

In the conceptual framework, current adaptive capacity is defined as the set of feasible adaptation actions. Therefore, identifying current adaptive capacity requires the decision maker to understand which actions are feasible. As the name suggests, feasibility studies may be carried out to identify the current set of feasible adaptation actions. For example, the financial limitations posed by budgetary constraints could indicate whether an action is feasible or not. If the decision maker is aware of boundary for feasible adaptation actions, then they can implicitly determine current adaptive capacity. However, it is recognised that using feasibility studies to determine every feasible adaptation action may be resource intensive, given the potential number of actions. Therefore, feasible studies could target particular determinants of adaptive capacity, rather than adaptive capacity as a whole.

The determinants of adaptive capacity need to be assessed in order to understand the limits of current adaptive capacity and how adaptive capacity might change. Tol and Yohe (2002) define eight determinants of adaptive capacity that are applicable to a number of contexts (see Figure 9).

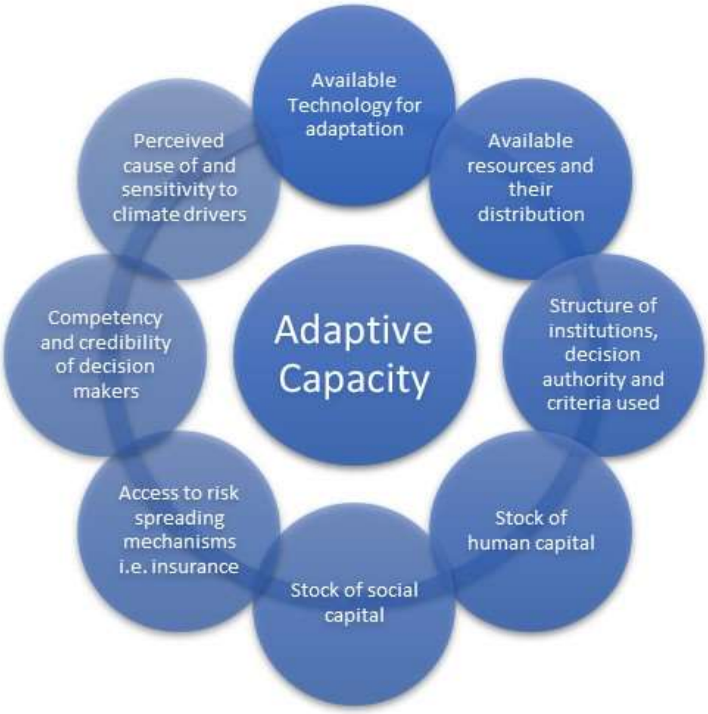

Figure 9: Possible determinants of adaptive capacity. Source: (Tol and Yohe, 2002).

The IPCC (2001) proposes six determinants of adaptive capacity, which broadly cover the same aspects as those highlighted above. Regardless of which list of determinants is applicable, it is clear that a multi-dimensional approach is needed to assess adaptive capacity. It is also important to understand the interaction between these determinants, as highlighted by Tol and Yohe (2002, 2007). Their “weakest link hypothesis” suggests the least developed determinants of adaptive capacity are not always compensated by the strongest determinants, which limits the resilience of a system to climate stresses. For example, a country may have good healthcare, but if there is no early warning system to inform individuals about an incoming hurricane then hospitals may not be able to cope with the demand following the hurricane. Therefore, the decision maker shouldn’t focus on one determinant of adaptive capacity to reduce vulnerability to climate stresses. Above all, identifying the determinants of adaptive capacity and their interaction is necessary to identify the current resources and constraints the decision maker faces, and their ability to influence adaptive capacity through changing these resources and constraints.

The state-of-the-art for the assessing the determinants of adaptive capacity are indicator-based approaches. These use indicators of vulnerability to different climate stressors. A number of studies use indicators in an attempt to identify relevant determinants, including Tol and Yohe (2002), Adger et al. (2004) and Hinkel (2011). For examples of these indicators, a list suggested by Brooks et al. (2005) is provided in Annex 3. However, Fussel (2009) argues that indicator-based assessments of adaptive capacity are often context specific and some are methodologically flawed. Therefore, a more generalised and rigorous approach for assessing adaptive capacity should be developed. In addition, Adger and Vincent (2005) recognise that the processes by which adaptive capacity is determined are not fully understood. As a result, the literature struggles to agree on a uniform set of determinants. Therefore, the current techniques used to assess adaptive capacity require the decision maker to carry out an assessment of the indicators of adaptive capacity that are applicable to their own decision making context.

Moreover, indicator-based assessments may be difficult to practically apply to the conceptual framework (Smit and Wandel, 2006). Adaptive capacity is defined as the set of feasible adaptation actions in the conceptual framework. This bottom-up definition contradicts the top-down approach of adaptive capacity indices. Indices implicitly measure adaptive capacity through indicators of vulnerability to specific climate stressors. Therefore, they cannot identify the explicit set of feasible adaptation actions which is defined in the conceptual framework.

However, it is recognised that indicator-based approaches may give the decision maker insights about how adaptive capacity might change in response to the endogenous and exogenous factors defined in the conceptual framework. The decision maker should attempt to assess which determinants they can influence, and which are out of their control. This will allow them to propose system-wide actions that best target these determinants, leading to improved adaptive capacity. It will also allow them to better predict how adaptive capacity might change in response to any system-wide actions they implement and any exogenous determinants, such as the climate pathway.

Once current adaptive capacity and the determinants of adaptive capacity have been assessed, the decision maker should estimate changes in adaptive capacity related to exogenous factors. This allows the decision maker to control for the exogenous determinants of adaptive capacity. Representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) could be used to predict the likely impact of exogenous factors on adaptive capacity. The IPCC fifth assessment report uses these pathways for their assessment of the change in climate and non-climate drivers (IIASA, 2014). Figure 10 shows the predicted impact of two of these RCPs on the change in global average surface temperature and precipitation.

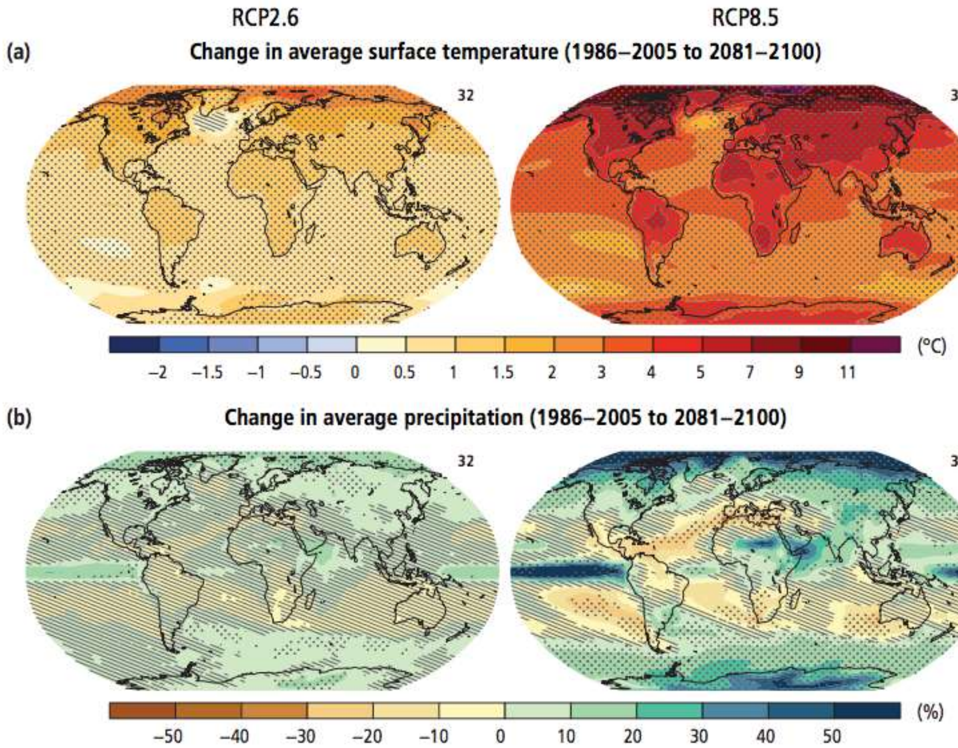

Figure 10: Change in average surface temperature (a) and change in average precipitation (b) based on multi-model mean projections for 2081-2100 relative to 1986-2005 under RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right hand corner of each panel. Stippling (i.e. dots) shows regions where the projected climate change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e. diagonal lines) shows region where the projected change is less than one standard deviation of the natural internal variability. Source: Figure SPM.7 (IPCC, 2014f).

Therefore, the impact of various pathways on climate and non-climate drivers could be used to assess changes in adaptive capacity. For example, an increased frequency of extreme weather events could decrease adaptive capacity as a result of damages to physical infrastructure. In addition, the expected level of autonomous adaptation should also be assessed. For instance, households may become increasingly aware of the specific climate risks that will affect them, and as a result they may be more willing to autonomously adapt to these risks. Leary (1999) accounts for this in his benefit-cost framework for assessing adaptation actions. Ultimately, the decision maker will have a better picture about the expected change in adaptive capacity if they account for more exogenous factors. This will then allow them to estimate the expected impact of their adaptation actions on future adaptive capacity.

4.2 Appraising System-wide Actions

Once current and expected future adaptive capacity have been assessed, the next step is to appraise the system-wide action. This step looks to determine the benefits and costs associated with the system-wide action. However, there are several factors that make the analysis of the benefits and costs uncertain. These are:

1. The change in adaptive capacity attributed to the system-wide action;
2. The possible future climate and non-climate pathway; and,
3. The appropriate valuation techniques for the benefits and costs.

Factors 1 and 2 become increasingly uncertain for adaptation actions with longer time horizons. In addition, the complexity of human and natural systems makes it hard to assess these two factors. Factor 3 depends on whether market or nonmarket valuation techniques are appropriate to use, and what type of discount rates should be used. Each factor is discussed respectively.

The change in adaptive capacity attributed to the system-wide action may be difficult to identify. This is because exogenous factors cloud the process by which adaptive capacity changes. This is a problem as it makes it hard to define the indirect benefits associated with system-wide actions (see section 2.2). Section 4.1 suggests that the decision maker should first evaluate how these exogenous factors are expected to impact adaptive capacity. Following on from this, the decision maker should assess how the system-wide is expected to change adaptive capacity in light of these benchmark exogenous changes. If changes in adaptive capacity aren't deterministic, multiple scenario analysis may help the decision maker conjecture different possible changes in adaptive capacity related to exogenous factors (Ranger et al., 2010; Willows and Connell, 2003). From these benchmark scenarios, the impact of the system-wide action on adaptive capacity could be assessed. For example under SSP4, which stipulates that inequality dominates the future socioeconomic pathway, the decision maker may infer that adaptive capacity is expected to decrease (IIASA, 2012). In this pathway, the effectiveness of the system-wide action at building adaptive capacity may be constrained. Therefore, the decision maker needs to estimate how the system-wide action will impact adaptive capacity in light of the possible future pathways.

In addition, the future climate and non-climate pathway may be uncertain. This is a problem because the benefits and costs associated with an adaptation action are contingent on the realised future pathway. For example, the benefits of the flood defences in section 3.2 are contingent on whether a high average rainfall or low average rainfall pathway is realised. Therefore, the decision maker may need to account for the benefits and costs in multiple future pathways using robust procedures (MEDIATION, 2013). From a practical point of view, this is brings in subjectivity and makes the decision making process less precise. However, given the current discourse on RCPs and SSPs this type of approach is the state-of-the-art (IIASA, 2011; IPCC, 2014f). Therefore, the probabilistic approach outlined in the conceptual framework may not be applicable to decision making contexts of deep uncertainty. Robust approaches are better suited to evaluate benefits and costs in these situations.

The techniques used to actually value the benefits and costs of the system-wide action also need to be considered. Standard economic benefit-cost analysis requires the benefits and costs to be monetised (Ranger et al., 2010). However, some values are easier to monetise than others. For example, concrete used to build a flood defence may have a market value and therefore be easy to cost. In contrast, the benefits that insect pollination provides do not have a market value, and so the value of losing this ecosystem service is harder to identify (Gallai et al., 2009). Therefore, nonmarket valuation techniques[9] can provide decision makers with more accurate information about wider changes in benefits and costs associated with system-wide actions. Furthermore, nonmarket valuation techniques may be more accurate at analysing benefits and costs than market valuation techniques (Pearce, 2002). This is because the monetary value exchanged in a market transaction does not necessarily reflect the value an individual attains from that transaction. Therefore, to evaluate changes in welfare it may be better for the decision maker to use nonmarket valuation techniques. In cases where a monetary value cannot be assigned, alternative assessments should be used such as scoring (Willows and Connell, 2003).

Finally, the appropriate discount rate needs to be used to ensure the benefits and costs can be compared as present values. For private decision making contexts this is the cost of capital. For public decision making contexts this is the social discount rate (Moore et al., 2013). The cost of capital is relatively easy to determine, for example by using market interest rates. However, the social discount rate is harder to identify. The HM Treasury (2015) recommends an annual discount rate of 3.5% for public projects up to 30 years. Thereafter, it recommends a periodically decreasing discount rate. This accounts for intergenerational transfers and increasing uncertainty. However, the exact social discount rate used for public project appraisal should reflect the specific societal rate of time preference. Therefore, the appropriate discount rate to use depends on the decision making context.

[9] The three main categories of nonmarket valuation are hedonic pricing, travel costing and contingent valuation (Pearce, 2002).

The evaluation of the system-wide action's benefits and costs should attempt to reduce the uncertainty associated with the factors highlighted above. It is important that the benefits and costs are valued in a way that is comparable to alternative adaptation actions. For example, the benefits and costs may be in present values. Using consistent approaches for evaluating adaptation actions will help the decision maker make a reliable comparison of the system-wide action to the alternatives. Possible evaluation techniques are outlined in section 4.3.

4.3 Decision Procedures

Once the alternative adaptation actions have been formally evaluated, the final step handles the decision making process. The appropriate process to follow will depend on the decision making context e.g. risk or uncertainty. A clear decision making process will provide a strong platform for the comparison of alternative adaptation actions.

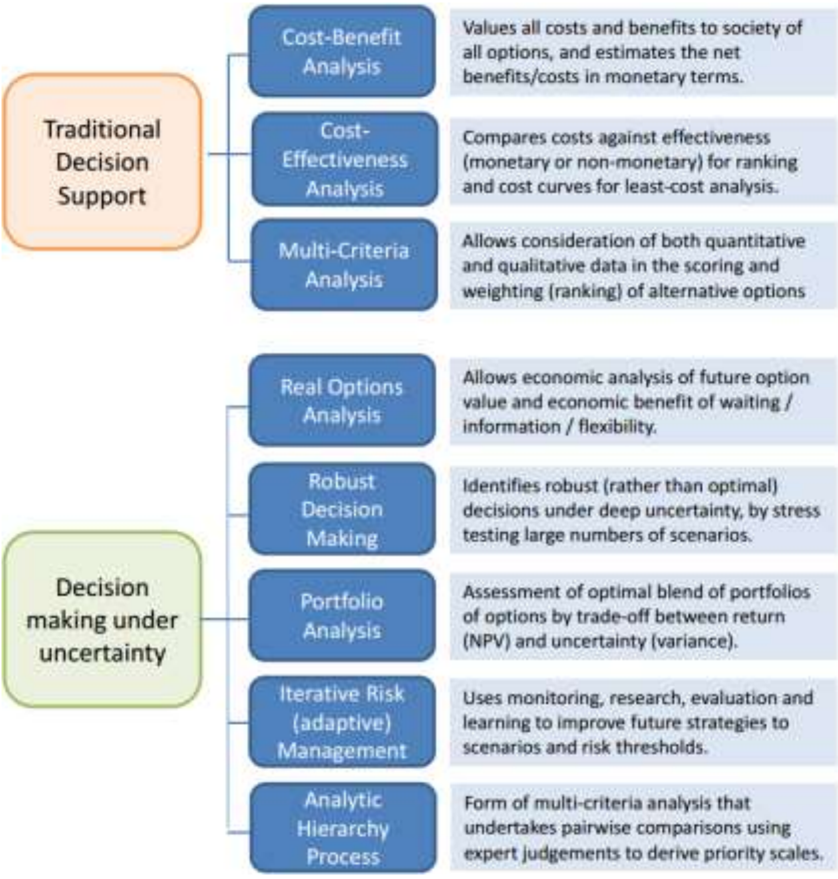

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Figure 11: Summary of decision support tools for decision making under uncertainty and risk. Source: Figure 2 in Deliverable 3.4 (MEDIATION, 2013).

Decision criteria need to be distinguished from decision support tools. Decision criteria are outlined in the conceptual framework and Annex 1. They are the benchmark from which to evaluate the adaptation actions. The criteria used depends on the decision maker's objectives, preferences and context. For example, when the outcomes of alternative actions are directly comparable, a decision criterion with a single parameter can be used. However, when the outcomes aren't comparable, a multiple criteria approach should be used (Willows and Connell, 2003). In contrast, decision support tools relate to the actual methods used to evaluate the actions. For example, the decision maker could use a combination of quantitative and qualitative analysis to reach conclusions about which adaptation actions best meet the chosen criteria. Therefore, decision support tools are the techniques used to assess adaptation actions relative to the decision criteria.

The MEDIATION (2013) project provides a useful assessment of the tools available to decision makers. The project distinguishes between traditional tools and those which may be more applicable for the evaluation of adaptation actions. The distinction primarily focuses on the level of risk or uncertainty in the decision making context. Traditional support tools focus on decision making under risk, and follow optimisation procedures. However, because probabilistic climate information may be limited or unreliable, traditional optimisation procedures might not be relevant (Dessai and Hulme, 2004). Therefore, alternative robust tools for decision making under uncertainty may be applicable. Figure 11 shows MEDIATION's (2013) summary of decision support tools.

Therefore, the appropriate decision support tools used to compare alternative adaptation actions to the decision criteria is context specific. Once the chosen adaptation actions have been implemented, it is recommended that periodical monitoring and evaluation takes place (Ranger et al., 2010). This will inform the decision maker about the success or failure of an adaptation action. As a result, they may be able to correct any problems with the current implemented actions and learn about improving future adaptation actions. This iterative approach is widely accepted in the literature on adaptation decision making (MEDIATION, 2013; Ranger et al., 2010; Watkiss, 2015; Willows and Connel, 2003).

5 Summary

Adaptation actions target climate drivers, by attempting to reduce vulnerability to climate risks and acting on climatic opportunities. The two categories of adaptation actions, sector-specific and system-wide, achieve these goals by different means; sector-specific actions directly target climate drivers, whereas system-wide actions indirectly target climate drivers. The framework provides a process that decision makers can follow in order to make reliable comparisons between these types of adaptation actions. It is hoped that this process will improve the representation of system-wide actions in the adaptation discourse.

The framework formally distinguishes between system-wide and sector-specific actions to clarify the differences between them (section 2). This formal distinction also helps explain the process for evaluating system-wide actions; the indirect benefits associated with system-wide actions can be determined by assessing how they change adaptive capacity. The framework suggests that the value of adaptation actions facilitated by a system-wide action (through building adaptive capacity) should be indirectly attributed to it. These are the indirect benefits of system-wide actions that the framework helps identify. This is particularly relevant for economic appraisals of adaptation actions, where the full benefits and costs associated with an action need to be evaluated before deciding between alternatives. Otherwise a misallocation of resources can occur, which is known as maladaptation in the climate change context. Therefore, the framework plays an essential part in helping decision makers avoid maladaptation, by ensuring they can reliably compare system-wide actions with alternative adaptation actions.

In addition, the framework accounts for the problem of additionality for both system-wide and sector-specific actions. By categorising the benefits and costs of adaptation actions into groups relating to both climate and non-climate drivers, decision makers can identify how different objectives are targeted by adaptation actions. This is particularly important for system-wide actions, which are likely to target non-climate objectives more than sector-specific actions. It is also relevant for overseas development assistance, where sustainable development, mitigation and adaptation are often seen as separable issues for the purpose of funding. However, the framework helps clarify that adaptation actions may have co-benefits (and co-costs) relating to objectives other than adaptation. Again, this will help decision makers identify the full benefits and costs associated with adaptation actions, and allow them to make more reliable comparisons between the alternatives.

The implications of different decision making contexts for the framework have also been discussed. The application in section 3 evaluates the system-wide action of developing new climate change scenarios, and their impact on the decision maker's adaptation actions in response to flood risks. The main application shows how the system-wide action can be evaluated in a deterministic context, whereas the extension shows how it can be assessed in a context of risk. By accounting for the indirect benefits that the new scenarios provide, both contexts show how the system-wide action can be more reliably compared to alternative adaptation actions. As a result, the possibility of maladaptation is reduced. Whilst this application may not share all the features of a realistic decision making context, it provides a starting point for applying the framework to real-world case studies and further testing its validity. Wider decision making contexts are considered in sections 2.3 and 4. These help establish the framework's relevance for evaluating adaptation actions in realistic decision making settings.

Finally, the limitations of the economic benefit-cost framework have been accounted for. It is recognised that traditional economic decision criteria and support tools may not be suitable for adaptation actions. This is because the long time horizons and complex processes associated with climate change and variability create uncertainty in predicting the future pathway, which makes the benefits and costs of adaptation actions difficult to determine. Therefore, decision criteria and support tools that are better suited for dealing with uncertainty have been applied to the framework. The framework remains relevant for contexts with different levels of uncertainty, as decision makers still need to make comparisons between alternative adaptation actions by estimating their benefits and costs. A broad range of other practical considerations are also addressed, including the measurement of adaptive capacity and appropriate valuation techniques. It is hoped that by applying the framework to real-world case studies, wider practical concerns will be highlighted and the validity of the framework can be further demonstrated.

6 References

Adger, W.N. and J. Barnett, 2009. Four reasons for concern about adaptation to climate change. *Environment and Planning A*, 41 (12), pp. 2800-2805. doi:10.1068/a42244.

Adger, W.N. and N. Brooks, 2004. Assessing and enhancing adaptive capacity. Cambridge University Press. *United Nations Development Programme*, Technical Paper 7 in “Adaptation policy frameworks for climate change: Developing strategies, policies and measures”, pp. 165-181.

Adger, W.N., Brooks, N., Bentham, G., Agnew, M. and S. Eriksen, 2004. New indicators of vulnerability and adaptive capacity. *Tyndall Centre Technical Report 7*. Available at: http://www.tyndall.ac.uk/publications/technical_reports (accessed 11.02.16).

Adger, W.N. and K. Vincent, 2005. Uncertainty in adaptive capacity. *Comptes Rendus Geoscience* 337 (4), pp. 399-410. doi:10.1016/j.crte.2004.11.004.

Armitage, D. and R. Plummer, 2010. Adaptive capacity and environmental governance. *Springer-Verlag Berlin Heidelberg*, Springer Series on Environmental Management, p. 115. doi: 10.1007/978-3-642-12194-4.

Arrow, K.J., 1963. Social choice and individual values. *Yale University Press,* 2nd ed. ISBN:0-300-01364-7.

Asteriou, D. and S. Price, 2005. Uncertainty, investment and economic growth: Evidence from a dynamic panel. *Review of Development Economics*, 9 (2), pp. 277-288. doi:10.1111/j.1467-9361.2005.00276.x.

Boardman, A.E., Greenberg, D.H., Vining, A.R. and D.L. Weimer, 2011. Cost-benefit analysis: Concepts and practice. *Prentice Hall, 4th* ed., Pearson series in economics. ISBN:0-13-143583-3.

Bronen, R. and F. S. Chapin III. 2013. Adaptive governance and institutional strategies for climate induced community relocations in Alaska. *Proceedings of the National Academy of Sciences*, 110 (23), pp. 9320-9325. doi:10.5751/ES-07801-200336.

Brooks, N., 2003. Vulnerability, risk and adaptation: A conceptual framework. *Tyndall Centre for Climate Change Research,* Working Paper No.38, pp. 11-13. Available at: http://www.tyndall.ac.uk/working_papers/working_papers.shtml.

Brooks, N., Adger, W.N. and P.M. Kelly, 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*, 15 (2), pp. 151-163. doi:10.1016/j.gloenvcha.2004.12.006.

Burch, S., 2010. Transforming barriers into enablers of action on climate change: Insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, 20 (2), pp. 287-97. doi:10.1016/j.gloenvcha.2009.11.009.

Chuku, C.A., 2009. Pursuing an integrated development and climate policy framework in Africa: options for mainstreaming. *Mitigation and Adaptation Strategies for Global Change*, 15 (1), pp. 41-52. doi:10.1007/s11027-009-9203-8.

Dessai, S. and M. Hulme, 2004. Does climate adaptation policy need probabilities? *Climate Policy*, 4 (2), pp. 107-128. doi:10.1080/14693062.2004.9685515.

Downing, T.E., 2012. Views of the frontiers in climate change adaptation economics. *WIREs Climate Change*, 3, pp. 161–170. doi: 10.1002/wcc.157.

Dixit, A. and R. Pindyck, 1994. Investment under uncertainty. *Princeton University Press*. ISBN:9780691034102.

Environment Agency, 2012. Thames estuary 2100 plan: Managing flood risk through London and the Thames estuary. *UK Government*. Available from: https://www.gov.uk/government/publications/thames-estuary-2100-te2100 (accessed 29.01.16).

Frankhauser, S. and I. Burton, 2011. Spending adaptation money wisely. *Climate Policy*, 11 (3), pp. 1037-1049. doi:10.1080/14693062.2011.582389.

Fussel, H.M., 2009. Development and climate change: Review and quantitative analysis of indices of climate change exposure, adaptive capacity, sensitivity, and impacts. *World Bank,* Working Paper 52059. Background note to the World Development Report 2010. Available at: http://www.worldbank.org/reference/ (accessed: 11.02.16).

Gallai, N., Salles, J.M., Settele, J. and B.E. Vaissiere, 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*, 68 (3), pp. 810-821. doi:10.1016/j.ecolecon.2008.06.014.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. *Global Environmental Change*, 19 (2), pp. 240-257. doi: 10.1016/j.gloenvcha.2008.12.003

Hallegatte, S., Lecocq, F. and C. de Perthuis, 2011. Designing climate change adaptation policies: An economic framework. *World Bank*, Policy Research Working Paper 5568.

Hallegatte, S., Shah, A., Lempert, R., Brown, C. and S. Gill, 2012. Investment Decision Making Under Deep Uncertainty: Application to Climate Change. *World Bank*, Policy Research Working Paper 6193.

Hinkel, J., 2011. “Indicators of vulnerability and adaptive capacity”: Towards a clarification of the science-policy interface. *Global Environmental Change*, 21 (1), pp. 198-208. doi: 10.1016/j.gloenvcha.2010.08.002.

HM Treasury, 2015. The Green Book. *Her Majesty’s Treasury of the UK government*. Available at: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent (accessed 02.02.16).

IIASA, 2011. New Scenarios. *International Institute for Applied Systems Analysis*. URL: http://www.iiasa.ac.at/web/home/research/Climate-Change-Scenarios.en.html (accessed 02.02.16).

IIASA, 2012. Shared Socioeconomic Pathways: Linking climate change & socioeconomic development. *International Institute for Applied Systems Analysis.* URL: www.iiasa.ac.at/web/home/resources/publications/options/ClimateChange.en.html (accessed 04.02.16).

IIASA, 2014. New Scenarios. *International Institute for Applied Systems Analysis* Publ. URL: http://www.iiasa.ac.at/web/home/research/Climate-Change-Scenarios.en.html (accessed 01.02.16).

IPCC, 2001. Climate Change 2001: Adaptation to climate change in the context of sustainable development and equity – Enhancing Adaptive Capacity. *Intergovernmental Panel on Climate Change,* Third Assessment Report, WGII, Chapter 18. URL: https://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp=653#186 (accessed 31.01.16).

IPCC, 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability – Adaptation Needs and Options. *Intergovernmental Panel on Climate Change*, Fifth Assessment Report, WGII, Chapter 14. URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap14_FINAL.pdf (accessed 31.01.16).

IPCC, 2014b. Climate Change 2014: Impacts, Adaptation, and Vulnerability – Glossary. Intergovernmental Panel on Climate Change, Fifth Assessment Report, WGII, Annex II. URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-AnnexII_FINAL.pdf (accessed 29.01.16).

IPCC, 2014c. Climate Change 2014: Impacts, Adaptation, and Vulnerability – Economics of Adaptation. *Intergovernmental Panel on Climate Change*, Fifth Assessment Report, WGII, Chapter 17. URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap17_FINAL.pdf (accessed 01.02.16).

IPCC, 2014d. Climate Change 2014: Impacts, Adaptation, and Vulnerability - Climate-resilient pathways: adaptation, mitigation, and sustainable development. *Intergovernmental Panel on Climate Change*, Fifth Assessment Report, WGII, Chapter 20. URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap20_FINAL.pdf (accessed 29.01.16).

IPCC, 2014e. Climate Change 2014: Impacts, Adaptation, and Vulnerability – Adaptation Opportunities, Constraints, and Limits. *Intergovernmental Panel on Climate Change*, Fifth Assessment Report, WGII, Chapter 16. URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap16_FINAL.pdf (accessed 02.02.16).

IPCC, 2014f. Climate Change 2014: Synthesis Report. *Intergovernmental Panel on Climate Change*, Fifth Assessment Report, WGII, Synthesis Report. URL: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf (accessed 04.02.16)

Johnson, S.R. and M.T. Holt, 1997. The Value of Weather Information. *Cambridge University Press*, Economic Value of Weather and Climate Forecasts (Katz, R. and A. Murphy), pp. 75-108. ISBN:9780521435710.

Klinke, A. and O. Renn, 2002. A New Approach to Risk Evaluation and Management: Risk-based, Precaution-based and Discourse-based Strategies. *Risk Analysis*, 22, pp. 1071-1094. doi:10.1111/1539-6924.00274.

Klinke, A. and O. Renn, 2013. A Framework of Adaptive Risk Governance for Urban Planning. *Sustainability*, 5, pp. 2036-2059. doi:10.3390/su5052036

Leary, N., 1999. A Framework for Benefit-Cost Analysis of Adaptation to Climate Change and Climate Variability. *Mitigation and Adaptation Strategies for Global Change*, 4, pp. 307-318. doi:10.1023/A:1009667706027.

Lipsey, R.G. and K.A. Chrystal, 2007. Economics. *Oxford University Press*, 11th ed., glossary, p. 635. ISBN:9780199286416.

MEDIATION, 2013. Deliverable 3.4: Framework for costs, cost-effectiveness, and other methods (including taking into account uncertainties) for socio-economic assessment. *REC Publishing,* European Commission FP7, MEDIATION, Technical Report No. 3.4.

Met Office, 2012. Climate Change Glossary. *The Met Office (UK)*. URL: http://www.metoffice.gov.uk/climate-change/guide/glossary (accessed 01.02.16).

Millner, A. and R. Washington, 2011. What determines perceived value of seasonal climate forecasts? A theoretical analysis. *Global Environmental Change,* 21 (1), pp.209-218. doi:10.1016/j.gloenvcha.2010.08.001.

Mitchell, T. and T. Tanner, 2006. Overcoming the Barriers: Mainstreaming Climate Adaptation in Developing Countries. *Tearfund,* Climate Change Briefing Paper 1, Climate Change and Disasters Group, Institute of Development Studies.

Moore, M.A., Boardman, A.E. and A.R. Vining, 2013. More appropriate discounting: the rate of social time preference and the value of the social discount rate. *Journal of Benefit-Cost Analysis*, 4 (1), pp. 1-16. doi:10.1515/jbca-2012-0008.

von Neumann, J. & O. Morgenstern, 1944. Theory of Games and Economic Behaviour. *Princeton University Press*.

OECD 2011. Handbook on the OECD-DAC Climate Markers. *Organisation for Economic Cooperation and Development*. URL: http://www.oecd.org/dac/stats/48785310.pdf (accessed 29.01.16).

OED Online, 2015a. Oxford English Dictionary Online. *Oxford University Press*. URL: http://www.oed.com/view/Entry/174609?rskey=2xyswa&result=1#eid (accessed 31.01.16).

OED Online, 2015b. Oxford English Dictionary Online. *Oxford University Press*. URL: http://www.oed.com/view/Entry/196665?redirectedFrom=system (accessed 31.01.16).

Pearce, D., 2002. An Intellectual History of Environmental Economics. *Annual Review of Energy and the Environment*, 27 pp. 57-81. doi: 10.1146/annurev.energy.27.122001.083429

Ranger, N., Millner, A., Dietz, S., Frankhauser, S., Lopez, A. and G. Ruta, 2010. Adaptation in the UK: a decision-making process. *Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy*. Available at: http://www.lse.ac.uk/GranthamInstitute/publication/adaptation-in-the-uk-a-decision-making-process (accessed 01.02.16)

Savage, L.J., 1954. The Foundations of Statistics. *Wiley & Sons*, 2nd ed. ISBN:0-486-62349-1

Smit, B. and J. Wandel, 2006. Adaptation, adaptive capacity and vulnerability. *Global Environmental Change,* 16 pp. 282-292. doi:10.1016/j.gloenvcha.2006.03.008.

Stigler, G., 1950. The Development of Utility Theory I & II. *Journal of Political Economy*, 58, No. 4 pp. 307-327 and No. 5 pp. 373-396.

Tol, R.S.J. and G. Yohe, 2002. Indicators for social and economic coping capacity - moving toward a working definition of adaptive capacity. *Global Environmental Change,* 12 (1), pp. 25–40. doi:10.1016/S0959-3780(01)00026-7.

Tol, R.S.J. and G. Yohe, 2007. The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test. *Global Environmental Change*, 17 (2), pp. 218-227. doi: 10.1016/j.gloenvcha.2006.08.001.

Tompkins, E.L., Adger, W.N., Boyd, E., Nicholson-Cole, S., Weatherhead, K. and N. Arnell, 2010. Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental Change*, 20 (4), pp. 510-40. doi:10.1016/j.gloenvcha.2010.05.001.

Watkiss, P. and A. Hunt, 2011. Method for the UK Adaptation Economic Assessment (Economics of Climate Resilience). *Department for Environment, Food and Rural Affairs (UK)*, Deliverable 2.2.1.

Williamson, T.B., Hesseln, H. and M. Johnston, 2010. Adaptive capacity deficits and adaptive capacity of economic systems in climate change vulnerability assessment. *Forest Policy and Economics*, 24, pp. 48-54. doi: 10.1016/j.forpol.2010.04.003.

Willows, R. and R. Connell, 2003. Climate adaptation: Risk, uncertainty and decision-making. *UK Climate Impacts Programme,* in collaboration with the Department for Environment, Food and Rural Affairs and the Environment Agency (UK). URL: http://www.ukcip.org.uk/wp-content/PDFs/UKCIP-Risk-framework.pdf (accessed 01.02.16).

UKCIP, 2007. AdOpt (Identifying Adaptation Options). *UK Climate Impacts Programme*. URL: http://www.ukcip.org.uk/wp-content/PDFs/ID_Adapt_options.pdf (accessed 01.02.16).

UKCIP, 2014. Adaptation Options. *UK Climate Impacts Programme*. URL: http://www.ukcip.org.uk/wizard/adaptation-options/#.Vq-1YJOLS34 (accessed 01.02.16).

Annex 1: Decision criteria for different contexts (Ranger et al., 2010)

Decision method	Decision criteria	Preference assumptions	Information assumptions	Additional requirements
1. METHODS APPLICABLE WHEN PROBABILITIES ARE KNOWN				
Maximize expected value	Usually economic costs and benefits	Time discounting Risk neutral. Does not account for equity of outcomes[23]	Known probabilities over all future events. No learning.	Marginal costs and benefits, i.e. small relative to consumption.
Maximize expected utility	Consumption, broadly defined to include monetized valuations of non-monetary impacts	Time discounting. Utility function: Accounts for risk aversion and equity of outcomes.	As above.	
Multi-attribute utility theory and Multi-criteria decision analysis.	Many criteria, including non-monetary impacts.	As for expected utility, + assumptions about the interactions between criteria (e.g. independence).	Usually deterministic, i.e. applicable when accounting for multiple objectives is more important than accounting for uncertainty. If uncertainty is accounted for, requires joint probability distributions over all decision criteria.	
Quasi-option value and Real options analysis	As for expected utility or expected value.	As for expected value or expected utility.	Known probabilities, + a model of how probabilities change in response to new information.	Irreversible adaptation options (sunk costs), or costly to adjust to new information.
Decision method	**Decision criteria**	**Preference assumptions**	**Information assumptions**	**Additional requirements**
2. METHODS APPLICABLE WHEN EXACT PROBABILITIES ARE NOT KNOWN				
Maximin expected utility	As for Expected Utility	As for expected utility + Extreme ambiguity aversion (act as if the worst plausible probability distribution were correct)	Multiple plausible probability distributions.	
Smooth ambiguity model	As for Expected Utility	As above, but allows for any attitude to ambiguity.	Multiple plausible probability distributions, and weights on each of these distributions	
Maximin	Any	Ordinal ranking of outcomes[24]	No likelihood information	
Minimax Regret	Any	Cardinal ranking of outcomes[25]	As above	
Info-gap decision theory	Various	Does not rigorously account for preferences. Assumes satisficing[26] thresholds , i.e. acceptable levels of minimum performance/ maximum windfall.	A 'best guess' model of the decision environment, and a set of models that are 'close' to this best guess.	A method for measuring the distance between different models (an 'uncertainty model')

Annex 2: Net Present Value Calculations for the Flood Defence Investment

Table a:
Discounted Benefits and Costs

Year Incurred	Fixed Cost (£30 in Years 3-5)	Maintenance Costs (£5 in Years 6-30)	Benefits in Low Average Rainfall (£6 in Years 6-30)	Benefits in High Average Rainfall (£15 in Years 6-30)
1				
2				
3	£27.06			
4	£26.14			
5	£25.26			
6		£4.07	£4.88	£12.20
7		£3.93	£4.72	£11.79
8		£3.80	£4.56	£11.39
9		£3.67	£4.40	£11.01
10		£3.54	£4.25	£10.63
11		£3.42	£4.11	£10.27
12		£3.31	£3.97	£9.93
13		£3.20	£3.84	£9.59
14		£3.09	£3.71	£9.27
15		£2.98	£3.58	£8.95
16		£2.88	£3.46	£8.65
17		£2.79	£3.34	£8.36
18		£2.69	£3.23	£8.08
19		£2.60	£3.12	£7.80
20		£2.51	£3.02	£7.54
21		£2.43	£2.91	£7.28
22		£2.35	£2.81	£7.04
23		£2.27	£2.72	£6.80
24		£2.19	£2.63	£6.57
25		£2.12	£2.54	£6.35
26		£2.04	£2.45	£6.13
27		£1.98	£2.37	£5.93
28		£1.91	£2.29	£5.72
29		£1.84	£2.21	£5.53
30		£1.78	£2.14	£5.34
PV Total	£78.46	£69.38	£83.26	£208.15

Table b:
Main Application - Net Present Value (NPV)

Total Costs	£147.85
Total Benefits	£208.15
NPV	£60.31

Table c:
Extension - Subjective Expected Net Present Value [E(NPV)]

	Average Rainfall	
	Low	High
Total Cost	£147.85	£147.85
Total Benefit	£83.26	£208.15
NPV	-£64.58	£60.31
Probability	0.7	0.3
E(NPV)	-£27.12	

Table d:
Extension - Objective Expected Net Present Value [E(NPV)]

	Average Rainfall	
	Low	High
Total Cost	£147.85	£147.85
Total Benefit	£83.26	£208.15
NPV	-£64.58	£60.31
Probability	0.4	0.6
E(NPV)	£10.35	

Annex 3: Vulnerability Indices Shortlist (Brooks et al., 2005)

			Source
Economy	National wealth	GDP per capita (US$ PPP)	WB
	Inequality	GINI coefficient	WIID
	Economic autonomy	Debt repayments (% GNI<comma> averaged over decadal periods)	WB
	National wealth	GNI (total<comma> PPP)	WB
Health and nutrition	State support for health	Health expenditure per capita (US$ PPP)	HDI
	State support for health	Public health expenditure (% of GDP)	HDI
	Burden of ill health	Disability adjusted life expectancy	WHO
	General health	Life expectancy at birth	HDI
	Healthcare availability	Maternal mortality per 100<comma>000	HDI
	Removal of economically active population	AIDS/HIV infection (% of adults)	HDI
	Nutritional status	Calorie intake per capita	GRID
	General food availability	Food production index (annual change averaged over 1981–90 and 1991–99)	WB
	Access to nutrition	Food price index (annual change averaged over 1981–90 and 1991–99)	WB
Education	Educational commitment	Education expenditure as % of GNP	HDI
	Educational commitment	Education expenditure as % of government expenditure	HDI
	Entitlement to information	Literacy rate (% of population over 15)	HDI
	Entitlement to information	Literacy rate (% of 15–24 year olds)	HDI
	Entitlement to information	Literacy ratio (female to male)	HDI
Infrastructure	Isolation of rural communities	Roads (km<comma> scaled by land area with 99% of population)	WB/CISEIN
	Commitment to rural communities	Rural population without access to safe water (%)	HDI
	Quality of basic infrastructure	Population with access to sanitation (%)	HDI
Governance	Conflict	Internal refugees (1000s) scale by population	WB
	Effectiveness of policies	Control of corruption	KKZ
	Ability to deliver services	Government effectiveness	KKZ
	Willingness to invest in adaptation	Political stability	KKZ
	Barriers to adaptation	Regulatory quality	KKZ
	Willingness to invest in adaptation	Rule of law	KKZ
	Participatory decision making	Voice and accountability	KKZ
	Influence on political process	Civil liberties	FH
	Influence on political process	Political rights	FH
Geography and demography	Coastal risk	km of coastline (scale by land area)	GRID
Coastal risk	Population within 100 km of coastline (%)	GRID	
	Resource pressure	Population density	CIESIN
Agriculture	Dependence on agriculture	Agricultural employees (% of total population)	WB
	Dependence on agriculture	Rural population (% of total)	WB
	Dependence on agriculture	Agricultural employees (% of male population)	WB
	Dependence on agriculture	Agricultural employees (% of female population)	WB
	Agricultural self-sufficiency	Agricultural production index (1985<comma> 1995)	WB
Ecology	Environmental stress	Protected land area (%)	GRID
	Environmental stress	Forest change rate (% per year)	GRID
	Environmental stress	% Forest cover	GRID
	Environmental stress	Unpopulated land area	CIESIN
	Sustainability of water resources	Groundwater recharge per capita	GRID
	Sustainability of water resources	Water resources per capita	GRID
Technology	Commitment to and resources for research	R&D investment (% GNP)	WB
	Capacity to undertake research and understand issues	Scientists and engineers in R&D per million population	WB

ECONADAPT

The Economics of Adaptation

Funded by the European Union

Chapter Three: Climate Agreements: Strategic Interaction between Mitigation and Adaptation

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Deliverable number	
Work Package Number	
Submission date	13 November, 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	**Climate Agreements: Strategic Interaction between Mitigation and Adaptation**
Authors:	Michael Finus
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Date:	Submission Date
Contact details	Michael Finus
Work Package Number	WP
Deliverable number	D
Filename:	.doc
Document history:	Draft/ Final and version number
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

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Preliminaries

This report is a substantially extended version of two working papers: 1) Bayramoglu, B., M. Finus, and J.-F. Jacques, "Climate Agreements in a Mitigation-Adaptation Game. Bath Economic Research Papers, No. 51/16 and 2) 1) Bayramoglu, B., M. Finus, and J.-F. Jacques, L'Adaptation est-elle un Frein aux Accords Climatiques? Mimeo.

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Guidance and Qualifications

This report addresses WP2, sub-task 3. At the core of this report is a game-theoretic model which studies the formation of climate agreements in the light of adaptation and mitigation. It emphasizes the strategic interaction between these two strategies to address climate change and what this implies for the success of future climate treaties. We argue that this model will be regarded as a seminal model in the future as it is far more general than existing models. Some central results are illustrated with stylized Monte-Carlo simulations. However, the model could not yet been empirically calibrated as there is a lack of data of country specific cost and benefits of mitigation and in particular adaptation. Nevertheless, the qualitative insights derived from the current model allow to derive important policy conclusions already. Due to the complexity of the game-theoretic setting, and the focus on general analytical results, the issues of uncertainty and the heterogeneity of countries could not yet be addressed by the model itself as this has been originally anticipated in the work plan. We have therefore dedicated a final section in this report to results from less general models which are summarized. These works have so far only be published as working papers and hence some caution is warranted. We extract the main insights from these working papers, relate it to our work and put it in the current policy context. We will also indicate the direction of future work, based on our model.

1 Introduction

Climate change is probably one of the most important challenges of human mankind. The Kyoto Protocol signed in 1997 was the first global treaty with specific mitigation targets but turned out to be not sufficient to address global warming. After several years of negotiations, a successor protocol was recently signed in Paris. However, most scholars doubt that the Paris accord will be sufficient to keep the increase of the global surface temperature below 2 degrees Celsius, a widespread accepted target to avoid severe interference with the climate system.

Clearly, mitigation to address the cause of global warming is costly, participation in a climate treaty is voluntary and compliance is difficult to enforce. Due to the slow progress of curbing global warming, and the first visible impacts of climate change, in particular in developing countries, adaptation measures (like building dykes against flooding and installing air-conditioning devices against heat) have received more attention in recent years. This is reflected in the negotiations which were leading to the Paris accord but also in the scientific community, as for instance summarized by various recent reports by the Internal Panel on Climate Change (IPCC). In contrast to mitigation (i.e. reducing emissions), which can be viewed as a non-excludable public good, adaptation (i.e. amelioration of climate damages) is typically viewed as a private good; it only benefits the country in which adaptation measures are implemented.

Already the Cancun Adaptation Framework suggested the following actions:

- Providing technical support and guidance to the Parties;
- Sharing of relevant information, knowledge, experience and good practices;
- Promoting synergy and strengthening engagement with national, regional and international organizations, centres and networks;
- Providing information and recommendations, drawing on adaptation good practices, for consideration by the COP when providing guidance on means to incentivize the implementation of adaptation actions, including finance, technology and capacity-building;
- Considering information communicated by Parties on their monitoring and review of adaptation actions, support provided and received.

The Paris Agreement also places much emphasis on adaptation and suggests a Green Climate Fund to expedite support for the last developed countries. It further mentions technology development and Transfer. Article 7 mentions the goal “on adaptation of enhancing adaptive capacity, strengthening resilience and reducing the vulnerability to climate change”.

The key research question which we try to answer in this report is: how does adaptation, as an additional strategy to mitigation, affect the prospects of international policy coordination to tackle climate change?

At the outset, the answer is not straightforward when considering the following points. The "pessimists" may argue that adaptation will shift the focus away from mitigation. This argument holds at the political level but also at the economic level for the following reason. In the presence of adaptation, the benefits from mitigation are lower. Therefore, equilibrium mitigation levels will be lower. But this also means that the positive spillovers from cooperation are lower, reducing the importance and the need for cooperation.

The "optimists" may point out that lower equilibrium mitigation levels reduce the incentive to free-ride and at least lead to larger stable coalitions. This may be reinforced by the simple fact that having a second strategy available should reduce the costs of addressing an externality problem. In other words, in an optimal mix of mitigation and adaptation, for a given climate change damage target, the total cost are lower with adaptation than without.

We show that the arguments of optimists and pessimists are correct, but on balance, optimistic factors dominate the outcome. Though in relative terms the gains from cooperation which are obtained in a climate treaty may be lower with adaptation, in absolute terms they are higher. In the presence of adaptation, self-enforcing treaties may be larger than in a treaty which only focuses on mitigation. This may imply that even mitigation levels to which signatories commit in a climate treaty may be higher, despite mitigation and adaptation are substitutes. A crucial difference is that in the presence of adaptation, mitigation may longer be strategic substitutes, typically associated with the term “free-riding” or “easy-riding” but may become strategic complements, typically associated with the term matching behaviour. Such a matching behaviour makes it easier to form large stable coalitions. Of course, larger coalitions do not automatically imply higher global welfare, which requires a further analysis.

Technically, strategic substitutes show up in downward reaction functions in mitigation space whereas strategic complements who up in upward sloping reaction functions. In the context of climate change, the former case has been referred to as carbon leakage. This means that if signatories to a treaty reduce emissions unilateral, some of this positive effect is lost because non-signatories find it optimal to increase their emissions. The steeper reaction functions, the larger is this leakage effect which has been estimated to be between 10 and 40 percent (IPCC 2014). The larger the leakage effect, the less attractive it becomes for countries to join a climate treaty. Thus, if adaptation can reduce those leakage effects, and even transform this into an anti-leakage effect, this would be most welcome. Non-signatories increase their mitigation efforts as a reaction to increased mitigation efforts by signatories.

We show that the possibility of upward-sloping reactions functions arises when the marginal benefits from mitigation are strongly influenced by adaptation (and vice versa), i.e. the cross effects are very strong, which technically implies that the cross derivatives are large in absolute terms. That is, there is substitutional relationship between equilibrium mitigation and adaptation in a country which is sufficiently strong (indirect effect) compared to the subtitutional relationship between own and foreign mitigation levels (direct effect). We will relate this rather technical conditions to the degree of vulnerability and resilence of countries as well as their costs of adaptation in section 5.

This work is related to four strands of literature.

Firstly, there is large body of literature on the game-theoretic analysis of international environmental agreements (IEAs), which can be traced back to Barrett (1994) and Carraro and Siniscalco (1993) and of which the most influential papers have been collected in a volume by Finus and Caparros (2015), including a comprehensive overview. To a large extent, this literature focuses on mitigation exclusively. A main conclusion which emerges from this literature has been termed “the paradox of cooperation”, a term coined by Barrett (1994). Whenever cooperation would matter, agreements achieve little. Either self-enforcing treaties comprise only few signatories or if they comprise many signatories then the gains from cooperation are small. In the first instance, the degree of cooperation is small and hence a treaty only marginal improves upon the non-cooperative outcome. In the second instance, the degree of cooperation is large, but the difference between no and full cooperation is small, i.e. the degree of externality is small. This means signatories’ behaviour needs to change only marginally and it is for this reason why a large agreement is stable. This is a pessimistic result, very much in line with the record of most international environmental agreements, and in particular climate change. Whereas the Framework Convention on Climate Change was signed by almost all countries, it was only a declarations of intentions and did not make much of a difference by itself. In contrast, the Kyoto Protocol was signed by 38 countries only, was not ratified by the US and Canada left the agreement later, and hence was also not very successful in curbing climate change. One reason being that the major emitters like the US, China and India did not accept emission ceilings under this treaty.

The model of this report is particularly related to those recent papers, which analyze the impact of additional strategies to mitigation on the success of coalition formation, like R&D investment to reduce mitigation costs (El-Sayed and Rubio 2014, Battaglini and Harstad, 2016 and Harstad 2012) or to generate breakthrough technologies with zero emissions (Barrett 2006, and Hoel and de Zeeuw 2010). In terms of strategic implications, there are two interesting links. Because adaptation leads to lower equilibrium mitigation levels for a given coalition, this reduces the free-rider incentives and hence encourages participation in larger stable coalitions similar to the concept of modest emission reductions as analyzed in Barrett (2002), and Finus and Maus (2008). Moreover, like the papers (e.g. Finus and Rübbelke 2013) on ancillary benefits, strategies impact not only on public but also on private benefits (i.e. impure public goods).[10] However, there is a crucial difference: ancillary benefits imply one strategy (mitigation) having two independent effects (private and public), whereas in a “mitigation-adaptation game” there are two strategies, a private (adaptation) and a public (mitigation) strategy, with impacts that are linked.

The most obvious connection is of course to those recent papers which study mitigation and adaptation in a strategic context. Different from for instance Buob and Stephan (2011), Ebert and Welsch (2011, 2012), Zehaie (2009), Eisenack and Kähler (2016), we allow for more than two countries and study the formation of agreements. Different from some recent work by Barrett (2008) and Benchekroun et al. (2016) who study climate treaties, we work in a much more general framework and derive most result analytically. This also allows us to study the possibility of strategic complementarities in mitigation space, which is absent in their model but is an important factor when evaluating the policy implications of adaptation in the context of a climate agreement. Nevertheless, we will report on some interesting results obtained by this literature in section 6.

Secondly, there is a literature on non-convexities of negative externalities, including early contributions by Baumol and Bradford (1972), Laffont (1976) and Starrett (1972) and recent contributions by Heugues (2014). This literature is important in the context of adaptation but is mainly neglected. This literature does not consider agreement formation but points to the strategic interaction between public and private actions, which can result in non-convexities. This literature considers the possibility that private action that reduces the vulnerability to environmental damages or increases the resilience to pollution can lead to non-convex damage functions Noticing that any public bad game can be recasted in a public good game framework, where the latter is the setting of our model, this means non-concavity of positive externalities. We show that in our model, in the presence of amelioration through adaptation, the conditions for upward-sloping reaction functions in public good provision space are exactly

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10 Ancillary benefits, also called co-benefits and secondary benefits in the environmental economics literature, refers to the fact that some mitigation measures will reduce local pollutants as a by-product. In the public goods literature, this phenomenon has been referred to as joint production (e.g. Cornes and Sandler 1984).

those related to the non-concavity of an agent's payoff function with respect to other players' provision levels.

Thirdly, there is a large literature on the private provision of public goods (e.g. Bergstrom, Blume and Varian 1986, Cornes and Hartley 2007, and Fraser 1992). "Private" means non-cooperative with the possibility of cooperative agreements normally not being considered in this literature. Typically, agents maximize a utility function subject to a linear budget constraint, with utility being derived from the total level of public provision (which is the sum of individual contributions) and a private numeraire good.[11] Central conclusions which emerge are the underprovision of the public good in the non-cooperative equilibrium compared to a Pareto-optimal provision, the theorem of income neutrality, implying that a redistribution of income (within boundaries) will not affect the equilibrium total public good provision, and the fact that the difference between equilibrium provision and first best increases with the number of agents. The typical assumption is that both goods are normal goods, which gives rise to downward sloping reaction functions in public good provision levels. This assumption is convenient to prove uniqueness of the equilibrium public good provision vector. It has typically two further implications. The cross derivative of utility with respect to the public and private good is assumed to be of minor importance and the typical text book illustration assumes a Cobb-Douglas utility function which gives rise to positive cross derivatives (and downward sloping reaction functions). However, downward sloping reaction functions, usually associated with the term “easy-riding”, is not the only possibility as pointed out by Cornes and Sandler (1986, ch. 5). Moreover, it does not seem unrealistic to consider the possibility that the public good can be a superior good which would allow for the possibility of upward sloping reaction functions. For some environmental goods there is some evidence (e.g. Bergstrom and Goodman (1973), Boercherding and Deacon (1972) and Selden and Song (1994)) of income elasticities larger than 1. Our model essentially captures this possibility. However, different from most of the public goods literature, we do not assume a linear budget constraint with constant prices, but, in the tradition of the game-theoretic literature on environmental treaties, consider the more general case of (strictly) convex cost functions of private and public good provision and hence non-constant marginal costs.[12] It is important to note that in the mitigation-adaptation context it is very plausible to assume that the cross derivative of the benefits is negative. However, we will show that the absolute value of the derivative is what matters and not the sign to have upward sloping reaction functions in the public good provision space.

It is important to note that the role and the implications of the cross derivative for public good provision extends much beyond the specific context of a climate agreement in the presence of adaptation. For instance, member states of the European Community can either coordinate on policy issues like security, anti-terrorism, migration and social policy or pursue those issues nationally. That is, financial resources can either be transferred to Brussels or remain with national governments. In practice, national and international policy measures co-exist and the benefit of national (international) policy measures is often diminished by the quality of international (national) measures. Citizens can vote for improved flood protection through their local government or can invest directly into the protection of their houses. Similarly, they can vote for the improvement of the local policy force or invest in devices to secure their private

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11 This refers to the standard assumption of a pure public good with a summation technology. Alternative assumptions, like impure public goods are considered for instance in Cornes and Sandler (1994) and a departure from the summation technology, like weakest-link and best-shot technologies are analyzed for instance in Hirschleifer (1983).

12 This generalization comes at the cost that the problem can no longer be viewed in terms of income elasticities.

homes. Money can be devoted to build and maintain a public or a private swimming pool and farmers can invest either in their own machinery and irrigation devices or to become a member of a cooperative with access to shared facilities. In each of these examples, it is likely that the benefit of the private investment impinges on the benefits of the public investment and vice versa, i.e. the cross derivative is negative. In other cases, it can be expected that the cross derivative is positive. Public spending on improved infrastructure may increase the value of houses and hence makes the private investment in flood protection and security more valuable for home owners.

Fourthly, there is quite some literature that investigates complementarities in strategic games. From the survey by Vives (2005), it appears that complementarity does not need to be the result of special assumptions but there are many interesting economic problems with this feature, though the analysis is usually more complex, requires different tools for the analysis and may suffer from multiple equilibria. For our problem, it turns out that a slight modification of standard theorems is sufficient for the analysis and simple conditions give existence and uniqueness of equilibria.

In what follows, we set out our model and its assumptions in Section 2. We present results of our two stage coalition formation model in reverse order according to backwards induction in Section 3 and 4, respectively, and summarize our main results and policy conclusions in Section 5. Section 6 discusses policy issues which cannot directly be answered by our model by considering some other literature. Whereas sections 2 to 4 are technical in nature, section 5 summarizes the main results from these previous sections non-technically and puts them in a policy context.

2 Model

2.1 Preliminaries

The following model is a stylized representation of a treaty formation game which considers the implication of the strategic interaction of adaptation and mitigation. The model works with general benefit and cost functions and derives most results analytically. It phrases the problem in terms of benefits from total mitigations and individual adaptation and costs of mitigation and adaptation. Without loss of generality, the problem could also be analyzed as an emission game where environmental damages depend on total emissions and the level of adaptation, and, again with mitigation and adaptation cost functions. Both problems are dual. This alternative approach is used for instance in Ebert and Welsch (2011, 2012). The following model makes a couple of simplifying assumptions which will be briefly discussed.

The first assumption is that of symmetric players: all countries are assumed to have the same payoff function. This allows to derive most results analytically but does not allow to capture major differences across countries in terms of the costs and benefits from mitigation and adaptation. Those differences are important in reality and hence we will discuss possible results which could emerge from considering heterogeneity in section 6. On the one hand, we report on some preliminary insights derived from some recent working papers. On the other hand, we speculate how our results would change by considering such an extension.

The second assumption is that even though we consider that mitigation and adaptation strategically interact on the benefit side, we do not consider this for the cost side. That is, the cost of mitigation is not influenced by the level of adaptation and vice versa. Essentially, we assume perfect input markets with an elastic supply. For most countries this should be a valid assumption, in particular if we assume that the mitigation and adaptation sector are relatively small in the context of the entire economy. For an alternative assumption see Buob and Stephan (2011)

The third assumption is that because of the complexity that coalition formation adds to our model, we assume a static payoff structure, which does not capture the stock nature of greenhouse gases. This approach is quite frequent in the literature on treaty formation and seems appropriate if the focus is on the basic incentive structure of participating in international environmental treaties. In many instances, the qualitative results derived from static and dynamic models have not been really different in terms of the prospects to form successful treaties. But even leaving the game-theoretic aspects aside, also some basic insights related to cost-benefit aspects are not so different between the static and the dynamic version as we discuss in section 6.

2.2 Setting

We consider n players, which are countries in our context, $i=1,2,...,n$ with the payoff function of country i in the pure mitigation game (M-game) given by:

(1) $$\Pi_i(Q,q_i)=B_i(Q)-C_i(q_i)$$

and in the mitigation-adaptation game (M+A-game) by:

(2) $$\Pi_i(Q,q_i,x_i)=B_i(Q,x_i)-C_i(q_i)-D_i(x_i)$$

where it will turn out throughout the paper that the M+A-game can be viewed as a generalization of the M-game. We denote the set of players by N. In the richer M+A-game, country *i* cannot only choose its individual mitigation level q_i but also its adaptation level x_i within its (compact and convex) strategy space $q_i \in [0,q_i]$ and $x_i \in [0,x_i]$ with x_i and q_i sufficiently large. Country i's payoff comprises benefits, B_i, which depend on total mitigation, $Q = \sum_{j=1}^{n} q_i$, and in the M+A-game additionally also on its individual adaptation level, x_i; the cost of mitigation is denoted by C_i, and the cost of adaptation by D_i.

If there is no misunderstanding, we drop the index i as we assume that players are ex-ante symmetric, i.e. they have the same payoff function; if we need to stress that players are ex-post asymmetric, e.g. because they chose different strategies, we will use the index. Apart from assuming that all functions, including their first and second derivatives, are continuous in their variable(s), we make the following assumptions regarding the components of the payoff functions (with the understanding that all derivatives with respect to x are only relevant in the M+A-game) where subscripts denote derivatives, e.g. $B_Q = \frac{\partial B}{\partial Q}$ and $B_{QQ} = \frac{\partial^2 B}{\partial Q^2}$.

General Assumptions

Both Games:

a) $B_Q > 0,\ B_{QQ} \le 0,\ C_q > 0,\ C_{qq} > 0$.

b) $lim_{Q \to 0} B_Q > lim_{q \to 0} C_q > 0$.

M+A-Game:

c) $B_x > 0,\ B_{xx} \le 0,\ D_x > 0,\ D_{xx} \ge 0$.

If $B_{xx} = 0$*, then* $D_{xx} > 0$ *and vice versa: if* $D_{xx} = 0$*, then* $B_{xx} < 0$.

d) $B_{xQ} = B_{Qx} < 0$.

e) $lim_{x \to 0} B_x > lim_{x \to 0} D_x > 0$.

From a technical point of view, assumptions a and c reflect the standard assumptions of concave benefit and convex cost functions. We allow for the possibility that benefit functions can be linear such that we can revisit some simple examples, which have been considered in the literature on IEAs in the context of a pure mitigation game. We assume cost functions of mitigation to be strictly convex in order to ensure unique equilibrium mitigation levels. For adaptation, it turns out that this is not necessary. However, in assumption c, we state that if benefit functions are linear in adaptation, then adaptation cost functions must be strictly convex and vice versa. These properties of the benefit and cost functions together with assumption b and e rule out corner solutions as for instance in Kolstad (2007) in a pure mitigation game and in Barrett (2008) in a mitigation-adaptation game.

From an economic point of view, assumption a stresses that mitigation is a pure public good, i.e. the marginal benefit from mitigation depends on the sum of all (and not on individual) mitigation efforts. In contrast, assumption c stresses that adaptation is a pure private good, i.e. the marginal benefit from adaptation depends on the individual adaptation level of a country (and not on those of others). The interdependency between mitigation and adaptation is captured through assumption d. The marginal benefit from mitigation (adaptation) decreases with the level of adaptation (mitigation). For simplicity, such an interdependency is assumed away on the cost side. In order to stress this, we assume for clarity two separate cost functions.

The strategic interaction between countries is directly related to the (pure) public good nature of mitigation. Mitigation in country i generates benefits in country i but also in all other countries. Thus, mitigation levels generate positive externalities. Adaptation levels generate no direct externalities. However, they indirectly influence the strategic interaction among countries because, as will become apparent below: the higher the adaptation level in a country, the lower will be its mitigation level, irrespective whether country i acts independently or joins an agreement.

Finally note that the assumption of ex-ante symmetric players is very much in the tradition of the literature on coalition formation in general (Bloch 2003 and Yi 1997 for overviews) and on IEAs in particular (Finus and Caparros 2015 for an overview) due to the complexity of coalition formation. This does not preclude that players are ex-post asymmetric. As will become apparent below, signatories and non-signatories will typically choose different mitigation levels and hence will receive different payoffs.

We assume the General Assumptions to hold throughout the paper. If we make further assumptions, we will mention them explicitly. Our two-stage coalition formation game unfolds as follows.

Definition 1: Coalition Formation Game

Stage 1

All countries choose simultaneously whether to join coalition $P \subseteq N$ or to remain a singleton player. Countries $i \in P$ are called signatories and countries $j \notin P$ are called non-signatories.

Stage 2

All non-signatories $j \notin P$ choose their economic strategies in order to maximize their individual payoff and all signatories $i \in P$ do so in order to maximize the aggregate payoff to all coalition members. Choices of all players are simultaneous.

M-Game: Mitigation levels are chosen simultaneously.

M+A-game: Version 1: Mitigation and adaptation are chosen simultaneously. Version 2: Mitigation and adaptation are chosen sequentially; all players choose first mitigation and then adaptation.

Stage 1 is the cartel formation game, which originates from the literature in industrial organization (d'Aspremont et al., 1983) and has been widely applied in this literature (e.g. Deneckere and Davidson 1985, Donsimoni et al. 1986 and Poyago-Theotoky 1995; see Bloch 2003 and Yi 1997 for surveys) but also in the literature on IEAs (e.g. Barrett 1994, Carraro and Siniscalco 1993 and, Rubio and Ulph 2006; see Finus and Caparros 2015 for a survey). This game has also been called open membership single coalition game as membership in coalition P is open to all players and players have only the choice between joining coalition P or remaining a singleton.[13] Open membership may be defended on two grounds. In the context of the provision of a public good, it appears that one is more concerned about players leaving a coalition than joining it. Moreover, to the best of our knowledge, all international environmental treaties are of the open membership type. The assumption of a single coalition simplifies the analysis but is also in line with the historical records of IEAs with a single treaty.

Stage 2 follows the standard assumption in the literature on coalition formation (see Bloch 2003 and Yi 2003 for surveys): the coalition acts as a kind of meta player (Haeringer 2004), internalizing the externality among its members, whereas non-signatories act selfishly, maximizing their own payoff. We also follow the mainstream assumption and assume that signatories and non-signatories choose their economic strategies simultaneously.[14] In the M-game, the second stage is simple: an equilibrium mitigation vector $q^*(P)$ is derived, given that coalition *P* has formed. In the M+A-game, Version 1 and 2 reflect different possible assumptions about the timing of mitigation and adaptation. As both versions lead to the same second stage equilibrium economic strategies as we show below, our results are robust.[15] The two-stage coalition formation game is solved by backwards induction. In the second stage, given that some coalition $P \subseteq N$ has formed in the first stage, in the M+A-game, Version 1 determines simultaneously an equilibrium mitigation vector $q^*(P)$ and an equilibrium adaptation vector $x^*(P)$ as a Nash equilibrium between coalition P and all remaining players not in P. Version 2 may be broken down into stage 2a and 2b. In stage 2b the equilibrium adaptation vector is determined, again, as a Nash equilibrium between coalition P and the remaining singletons. Equilibrium adaptation levels in stage 2b will depend on the levels of mitigation chosen in stage 2a, which in turn depend on which coalition P has formed in stage 1. Hence, in stage 2b, we can write $x^*(q(P))$. Substituting this into the payoff function (1), payoffs in stage 2a are only a function of mitigation levels. This allows us to solve stage 2a for equilibrium mitigation levels, $q^*(P)$.

It is clear that we want for technical reasons for each possible coalition P a unique equilibrium strategy vector to exist. This allows us to write $\Pi_i^*(P)$ instead of $\Pi_i^*(q^*(P))$ in the M-game. and, accordingly, $\Pi_i^*(P)$ instead of $\Pi_i^*(q^*(P), x^*(P))$ in the M+A-game. Even though we provide sufficient conditions for existence and uniqueness only in the next section,

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13 Surveys of coalition games with other membership rules, including exclusive membership and multiple coalitions, are provided in Bloch (2003) and Yi (1997) and a systematic comparison of equilibrium coalition structures under different membership rules is conducted in Finus and Rundshagen (2009).

14 Again, see Bloch (2003) and Yi (2003) on this. This has been called Nash-Cournot assumption in the literature on IEAs and has been contrasted with the assumption of a sequential choice, called Stackelberg assumption, where signatories act as a Stackelberg leader. The Stackelberg assumption has been considered for instance in Barrett (1994) and Rubio and Ulph (2006) in a pure mitigation game.

15 In principle, we could also consider a Version 3 in which the timing is reversed compared to Version 2. Version 3 is considered in Zehaie (2009). However, assuming first adaptation and then mitigation is not in line with the historical development in climate change policy.

we make already use of this assumption in order to save on notation and define a stable coalition P^* as follows:

internal stability: $\Pi_i^*(P^*) \geq \Pi_i^*(P^* \setminus \{i\}) \quad \forall i \in P^*$

external stability: $\Pi_j^*(P^*) \geq \Pi_j^*(P^* \cup \{j\}) \quad \forall j \notin P^*$

It is evident that the conditions of internal and external stability de facto define a Nash equilibrium in membership strategies in the first stage. Each player i who announced to join coalition P^* should have no incentive to (unilaterally) change her strategy by leaving coalition P^* and each player j who announced not to join coalition P^* should have no incentive to (unilaterally) change his strategy and join coalition P^*, given the equilibrium announcements of all other players.

Note that by the construction of the coalition game, the equilibrium economic strategy vectors in the second stage correspond to the Nash equilibrium known from games without coalition formation if coalition P is empty or contains only one player. We also call this "no cooperation". By the same token, if coalition P comprises all players, i.e. the grand coalition forms, $P = N$, this corresponds to the "social optimum". We also call this "full cooperation". Any non-trivial coalition (i.e. a coalition of at least two players) which comprises more than one player but less than all players may be viewed as partial cooperation.

In order to evaluate the outcomes and to analyze the driving forces of coalition formation, we define some useful properties where p denotes the cardinality of P, i.e. the size of coalition P.

Definition 2: Superadditivity, Positive Externality and Cohesiveness

i) A game is (strictly) cohesive if for all $P \subset N$ *:*

$$\sum_{k \in N} \Pi_k^*(\{N\}) \geq (>) \sum_{k \in P} \Pi_k^*(P) + \sum_{l \in \{N \setminus P\}} \Pi_l^*(P)$$

(ii) A game is (strictly) fully cohesive if for all $P \subseteq N$ *, p≥2 and all* $i \in P$ *:*

$$\sum_{k \in P} \Pi_k^*(P) + \sum_{l \in \{N \setminus P\}} \Pi_l^*(P) \geq (>) \sum_{k \in \{P \setminus \{i\}\}} \Pi_k^*(P \setminus \{i\}) + \sum_{l \in \{N \setminus P \cup \{i\}\}} \Pi_l^*(P \setminus \{i\})$$

(iii) A coalition game exhibits a (strict) positive externality if for all $P \subset N$ *, p≥2 and for all* $j \in N \setminus P$ *:*

$$\Pi_j^*(P) \geq (>) \Pi_j^*(P \setminus \{i\})$$

(iv) A coalition game is (strictly) superadditive if for all $P \subseteq N$ *, p≥2 and all* $i \in P$ *:*

$$\sum_{k \in P} \Pi_k^*(P) \geq (>) \sum_{k \in \{P \setminus \{i\}\}} \Pi_k^*(P \setminus \{i\}) + \Pi_i^*(P \setminus \{i\})$$

Typically, a game with externalities is strictly cohesive, with the understanding that in a game with externalities the strategy of at least one player has an impact on the payoff of at least one other player. The reason is that the grand coalition internalizes all externalities by assumption. Hence, cohesiveness motivates the choice of the social optimum as a normative benchmark, and it is the basic motivation to investigate stability and outcomes of cooperative agreements. A stronger normative motivation is related to full cohesiveness as it provides a sound justification to search for large stable coalitions even if the grand coalition is not stable due to large free-rider incentives. The fact that large coalitions, including the grand coalition, may not be stable in coalition games with positive externalities is well-known in the literature (e.g. see the overviews by Bloch 2003 and Yi 1997). Examples of positive externality games include output and price cartels and the pure mitigation game. The positive externality can be viewed as a benefit generated by the coalition, which also accrues to outsiders as these benefits are non-excludable. This property makes it attractive to stay outside the coalition. This may be true despite superadditivity, a property which makes joining a coalition attractive. In the context of the pure mitigation game, stable coalitions are typically small because with increasing coalitions, the positive externality effect dominates the superadditivity effect.[16] Whether this is also the case if adaptation is available as a second strategy is one of the key research question of this paper.

Finally note that all four properties are related to each other. For instance, a coalition game which is superadditive and exhibits positive externalities is fully cohesive and a game which is fully cohesive is cohesive.

16 This is quite different in negative externality games. In Weikard (2009) it is shown that in a coalition game with negative externalities and superadditivity the grand coalition is the unique stable equilibrium.

3 Second Stage of Coalition Formation

3.1 Equivalence of Version 1 and 2 and Symmetry

In this subsection, we establish the equivalence between Version 1 and 2 in Definition 1 and some basic implications of the ex-ante symmetry assumption regarding equilibrium mitigation and adaptation levels in the second stage. We assume the existence of a unique interior second stage equilibrium for which we establish sufficient conditions in Subsection 3.2.

Lemma 1: Equivalence of Version 1 and 2 in the M+A-Game

In the M+A-game, Version 1 and 2 are equivalent in terms of an interior second stage equilibrium.

Proof: Version 1: The first order conditions in terms of mitigation are given by

(3) $$pB_Q(Q,x) = c_q(q)$$

where we may recall that p denotes the size of coalition $P \subseteq N$. For non-signatories we have $p = 1$ and for signatories $p \geq 2$ if a non-trivial coalition forms. The first order conditions for non-signatories and signatories in terms of adaptation are the same and are given by

(4) $$B_x(Q,x) = D_x(x)$$

Version 2: In the last stage, stage 2b, when signatories and non-signatories simultaneously choose their adaptation levels, the first order conditions of non-signatories and signatories are given by (4). These first order conditions implicitly determine adaptation x as a function of total mitigation Q. Hence, using $x(Q)$, the maximization problem, which signatories and non-signatories face in stage 2a, when choosing their mitigation levels, leads to the first order conditions $$p\left[B_Q(Q,x(Q) + B_x(Q,x(Q))\frac{\partial x}{\partial Q}\right] - C_q(q) - D_x(x(Q))\frac{\partial x}{\partial Q} = 0$$,

again with $p = 1$ and $p \geq 2$ for non-signatories and signatories, respectively, which, using the first order conditions (4) and rearranging terms, imply (3) above. **Q.E.D.**

The proof above made already use of the assumption of ex-ante symmetric players for notational simplicity but holds generally, also for asymmetric players. The first order conditions (3) and (4) are instructive in several respects, with the main conclusions summarized in Lemma 2 below. Firstly, only the strict convexity of the cost function of mitigation (General Assumptions, part a) ensures that mitigation levels among signatories are unique. From (4) it is evident that this is not required for adaptation. Secondly, the first order conditions in terms of adaptation are the same for non-signatories and signatories because adaptation is a private good. However, one should therefore not mistakenly conclude that policy coordination is not required in terms of adaptation. We will show later that equilibrium adaptation levels decrease in the size of the coalition and hence obtain their lowest levels in the social optimum. Moreover, adaptation influences optimal mitigation levels. Thirdly, all non-signatories choose the same mitigation level $q^*_{j \notin P}(p)$ and all signatories choose the same mitigation level $q^*_{i \in P}(p)$ for all p, $1 \leq p \leq n$. Moreover, $q^*_{j \notin P}(p) < q^*_{i \in P}(p)$ for all p, $1 < p < n$, and hence

$\Pi^*_{j\notin P}(p) > \Pi^*_{i\in P}(p)$. Finally, in the M-game, there is only one set of first order conditions, namely (3) and hence what we concluded in the last point is also true.

Lemma 2: Symmetry and Equilibrium Mitigation and Adaptation

Consider an arbitrary coalition and an interior second stage equilibrium.

M-Game: For all p, 1<p<n: $q^*_{j\notin P}(p) < q^*_{i\in P}(p)$ *with* $q^*_{j\notin P}(p) = q^*_{l\notin P}(p)$ *for all* $j,l \notin P$ *and* $q^*_{i\in P}(p) = q^*_{k\in P}(p)$ *for all* $i,k \in P$.

M+A-game: $x^*_{i\in P}(p) = x^*_{j\notin P}(p)$ *for all p, 1≤p≤n and all* $i,j \in N$. *Moreover, for all p, 1<p<n:* $q^*_{j\notin P}(p) < q^*_{i\in P}(p)$ *with* $q^*_{j\notin P}(p) = q^*_{l\notin P}(p)$ *for all* $j,l \notin P$ *and* $q^*_{i\in P}(p) = q^*_{k\in P}(p)$ *for all* $i,k \in P$.

Both games: $\Pi^*_{j\notin P}(p) > \Pi^*_{i\in P}(p)$ *for all p, 1<p<n.*

Proof: See Working Paper 1.

The importance of Lemma 2 derives from the fact that it compactly summarizes the implications of the simplification which are associated with the assumption of ex-ante symmetric players.

3.2 Existence of a Unique Interior Second Stage Equilibrium

In this subsection, we derive sufficient conditions for the existence of a unique interior second stage equilibrium for every possible coalition P of size p, *1≤p≤n*. We use the concept of replacement functions, which Cornes and Hartley (2007) have shown is a convenient and elegant tool to establish existence of a unique Nash equilibrium in aggregative games. We only have to slightly modify their approach in two respects. Firstly, we view the second stage equilibrium as a Nash equilibrium between coalition P, acting de facto as a single player, and all non-signatories, who play as singletons. Secondly, in the M+A-game, and different from the M-game and the cases considered in Cornes and Hartley's paper, we need to account for the possibility of upward-sloping replacement functions as explained below. In the following, we introduce the concept of reaction and replacement functions and sketch the arguments to establish existence and uniqueness of an interior equilibrium, providing additional formal details in Working Paper 1. We consider first the more comprehensive and interesting M+A-game, and briefly comment on the simpler M-game in passing. We know from the definition of the payoff function that the strategy space of each player is compact and convex and payoffs of all players are continuous and bounded in the entire strategy space. Hence, an equilibrium exists.

We first observe that the first order conditions in terms of adaptation (4) implicitly define the equilibrium adaptation levels as a function of total mitigation, $x(Q)$. Consequently, the first order conditions in terms of mitigation (3) can be written as $pB_Q(Q,x(Q)) = C_q(q)$. Now if we let $Q = q_i + Q_{-i}$, each first order condition implicitly defines q_i as a function of Q_{-i}, which is the reaction function of player i. Hence, generally, for any coalition $P \subseteq N$ we have

$q_{i \in P} = r_{i \in P}\left(Q_{-i}\right)$ for signatories and $q_{j \notin P} = r_{j \notin P}\left(Q_{-j}\right)$ for non-signatories (setting $p = 1$ in the first order conditions of non-signatories). Clearly, reaction functions are well-known and well-suited to study the strategic interaction among players and we will use them in the next subsection for exactly this reason. However, for the purpose at hand, and given that we consider more than two players and more than one strategy, the concept of replacement functions is much simpler.

For instance, if we use the first order conditions directly and derive the individual replacement function of signatories, $q_{i \in P} = R_{i \in P}\left(Q\right)$, and of non-signatories $q_{j \notin P} = R_{j \notin P}\left(Q\right)$. The aggregate replacement function is simply derived by summing over all individual replacement functions, i.e. $Q = R\left(Q\right) = \sum_{i \in N} R_i(Q)$. The idea is illustrated in Figure 1 for the assumption of downward sloping replacement functions.[17]

"Figure 1 about here"

"Figure 2 about here"

The graphical determination of the second stage equilibrium works as follows. Firstly, the aggregate replacement function is derived as the vertical summation of all individual replacement functions. Notice that due to symmetry all individual replacement functions of signatories are the same, and the same applies for all non-signatories. Secondly, the intersection of the aggregate replacement function with the 45^0-degree line, point E, determines the aggregate equilibrium mitigation level because there $Q^* = R\left(Q^*\right)$ by definition. Thirdly, one draws a vertical line from point E down to Q^* on the abscissa. Finally, from the intersection point with the individual replacement functions, points e and f in the graph, one draws horizontal lines to the ordinate which gives the equilibrium individual mitigation level of signatories $q^*_{i \in P}$ and non-signatories, $q^*_{j \notin P}$.

We note that if all individual replacement functions are continuous and downward sloping over the entire strategy space, also the aggregate replacement function will have this property. If all replacement functions start at a positive value on the ordinate, all equilibrium mitigation levels will be strictly positive. Finally, the aggregate replacement function will intersect only once with the 45^0-degree line if its slope is negative over the entire domain.

The idea of upward sloping reaction functions is illustrated in Figure 2. The procedure of determining the equilibrium works exactly the same, as discussed above. However, now the absolute value of the slope of the aggregate replacement function matters. Figure 2 illustrates that the aggregate replacement function could have a slope larger than 1 everywhere, in which case it will never intersect with the 45^0-degree line. Hence, the conditions which ensure that the aggregate replacement function has a slope less than 1 are those which ensure a unique interior equilibrium.

Additional Assumption

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17 The graph assumes linear replacement functions but this does not necessarily has to be the case and is not crucial for the following arguments.

Let $A := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}}$ *in the M+A-game. For all players* $i \in N$ *and* $x_i \in [0, \overline{x_i}]$ *and* $q_i \in [0, \overline{q_i}]$*:* $A := \left[\frac{p^2}{C_{qq}(q_{i \in p})} + \frac{(n-p)}{C_{qq}(q_{j \notin p})} \right] < 1$.

The left-hand side term in the inequality listed in the Additional Assumption above is the slope of the aggregate replacement function. The sign of this slope is related to the term $A^{M+A} := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}}$ in the M+A-game, which would be $A^M := B_{QQ}$ in the M-game. If $A < 0$, replacement functions are downward sloping and no further assumptions for uniqueness are necessary. This is also true if $A = 0$ in which case individual and aggregate replacement functions are horizontal lines and hence also intersect with the 45^0-degree line only once. In the M-game $B_{QQ} \leq 0$ and hence uniqueness follows immediately. In the M+A-game, A^{M+A} can also be negative or equal to zero, but could also be positive. It is for this last possibility why we introduce the Additional Assumption as a sufficient condition which ensures that the slope is strictly smaller than 1 over the entire strategy space.

Proposition 1: Existence of a Unique Interior Equilibrium in the Second Stage

Consider an arbitrary coalition of size p, 1≤p≤n.

M-Game: A unique interior equilibrium in the second stage always exists.

M+A-game: A sufficient condition for the existence of a unique interior equilibrium in the second stage, is either A≤0 or if A>0, then the Additional Assumption holds.

Proof: See Working Paper 1.

The importance of term A will also become apparent in the next subsection.

3.3 Strategic Interaction Between Mitigation and Adaptation

In this subsection, we analyze the strategic interaction among players in terms of mitigation and the strategic relation between mitigation and adaptation for a given coalition $P \subseteq N$ of size *p*, *1≤p≤n*. For this, we derive the slopes of the reaction functions which have been defined in the previous Subsection 3.2. For the subsequent analysis, we need to make only two additional remarks. Firstly, one can view the coalition as one player and because of symmetry all non-signatories as another player. Hence, if we define the aggregate reaction function of signatories by $Q_{i \in P} = r(Q_{j \notin P})$ and of non-signatories by $Q_{j \notin P} = r(Q_{i \in P})$, with $Q_{i \in P} = pq_{i \in P}$ and $Q_{j \notin P} = (n-p)q_{j \notin P}$, the total mitigation of signatories and non-signatories, respectively, in order to capture the strategic interaction between these two groups in a compact way. Secondly, the first order condition (4), $B_x(Q, x) = D_x(x)$, which is identical for all players, implicitly defines optimal adaptation as a function of total mitigation, $x = f_{i \in N}(Q)$.

Proposition 2: Slopes of Reaction Functions in Mitigation and Adaptation Space

Consider an arbitrary coalition of size p, 1≤p≤n, and let primes denote the slopes of reaction functions. Further let $A := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}}$ *in the M+A-game and* $A := B_{QQ}$ *in the M-game.*

Strategic interaction between mitigation levels in the M-game and M+A-game

The slopes of individual and aggregate reaction functions of signatories are given by $r'_{i\in P}(Q_{-i}) = \frac{pA}{C_{qq}(q_{i\in P}) - pA}$ *and* $r'(Q_{j\notin P}) = \frac{p^2 A}{C_{qq}(q_{i\in P}) - p^2 A}$*, respectively, and the slopes of non-signatories' reaction functions are given by* $r'_{j\notin P}(Q_{-j}) = \frac{A}{C_{qq}(q_{j\notin P}) - A}$ *and* $r'(Q_{i\in P}) = \frac{(n-p)A}{C_{qq}(q_{j\notin P}) - (n-p)A}$*.*

That is, reaction functions are always weakly downward sloping in the M-game. In the M+A-game, reaction functions are (weakly) downward sloping if A≤0 and are (strictly) upward sloping if A>0.

Strategic interaction between mitigation and adaptation in the M+A-game

For each possible coalition, the slope of the individual reaction function $x = f_{i\in N}(Q)$ *is given by* $f'_{i\in N}(Q) = \frac{B_{Qx}}{D_{xx} - B_{xx}} < 0$*.*

Proof: See Working Paper 1.

The first statement sheds light on whether mitigation levels are strategic substitutes or complements. In the M-game, they are always substitutes if we exclude the case $B_{QQ} = 0$ in which case reaction functions are orthogonal. In the M+A-game, this is also the case provided the term $A := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}}$ is negative, again with orthogonal reaction functions for the special case if $A = 0$. However, if $A > 0$, then reaction functions are upward sloping and mitigation strategies are strategic complements.[18] Because $B_{QQ} \leq 0$, $A > 0$ if $\frac{(B_{xQ})^2}{D_{xx} - B_{xx}} > 0$ is sufficiently large, which captures the interaction between mitigation and adaptation. Intuitively, this is evident when considering the first order condition (3), $pB_Q(q_i + Q_{-i}, x(q_i + Q_{-i})) = C_q(q_i)$, using $Q = q_i + Q_{-i}$. Increasing Q_{-i} in a comparative static way (and hence Q) has a direct negative effect on B_Q, namely reducing B_Q because of

18 It is easy to show that the signs of the slopes of reaction and replacement functions are the same, they only depend on the sign of the term A. The possibility of upward sloping reaction functions has been pointed out by Ebert and Welsch (2011, 2012) in a two-player model.

$B_{QQ} < 0$. Anything else being equal, this would call for a lower $C_q(q_i)$ in order for the equality to be able to hold and hence a lower q_i because $C_{qq} > 0$. However, there is also the indirect effect, which increases B_Q and hence calls for a higher q_i. Increasing Q_{-i} increases Q and calls for a lower $x(Q)$, which in turn increases B_Q because $B_{Qx} < 0$. This second indirect effect is exactly $\frac{(B_{xQ})^2}{D_{xx} - B_{xx}}$. It is important to note that even if the indirect effect dominates the direct effect, the sufficient conditions for the existence and uniqueness of second stage equilibria, as stated in the Additional Assumptions, do not need to be violated. Moreover, only the magnitude but not the sign of the cross derivative B_{xQ} matters.

An alternative way of viewing this problem is by noticing that the second derivative of the payoff function (2) with respect to other players' mitigation levels, after inserting $x(Q)$, is exactly term A. Thus, if $A > 0$, the payoff function is not concave but convex in other players mitigation level.

Upward sloping reaction functions could lead to more optimistic outcomes in a coalition formation game (i.e. larger coalitions). The intuition is that if mitigation levels are strategic substitutes, any additional increase of signatories' mitigation efforts is countervailed by a decrease of non-signatories' mitigation efforts. In the context of climate change, this has been called (carbon) leakage which makes it less attractive to join an agreement. Thus, upward sloping reaction functions may be viewed as a form of anti-leakage or matching, which may be conducive to form large stable coalitions.

The idea to relate the success of coalition formation to the slopes of reaction function is interesting. However, we have to be aware that up to now results have only been established for a given coalition P but nothing has been concluded how mitigation and adaptation changes with the degree of cooperation, which is the crucial point for the analysis of stable coalitions. We will analyze this in Section 4.

The last statement in Proposition 2 gives a clear answer to the question whether adaptation and total mitigation are substitutes or complements. They are always substitutes, irrespective of the degree of cooperation. Because the concept of substitutes and complements is not uniquely defined in the literature, Proposition 3 adds two variants to this.

Proposition 3: Alternative Views of the Strategic Interaction between Mitigation and Adaptation

Consider an arbitrary coalition of size p, 1≤p≤n and an interior second stage equilibrium in the M+A-game.

(1) Individual mitigation levels of non-signatories and signatories and hence also the total mitigation level are strictly lower in the M+A-game than in the M-game.

(2) Consider payoff function (1) but let the mitigation cost function be given by $\gamma C(q)$ *and the adaptation cost function by* $\delta D(x)$ *where* $\gamma > 0$ *and* $\delta > 0$ *are strictly positive parameters. Then individual mitigation levels of signatories and non-signatories and hence also the total*

mitigation level decrease (increase) in $\gamma(\delta)$ *and adaptation levels increase (decrease) in* $\gamma(\delta)$*.*

Proof: See Working Paper 1.

From the first statement we can conclude that if adaptation is available as a second strategy, less mitigation is required. Since mitigation concerns the public good part in this strategic game, one may conjecture that the incentive to leave a coalition could be less pronounced in the M+A-game than in the M-game. The driving force would be similar like in Barrett (2002) and Finus and Maus (2008) who show that modest emission reduction lead to larger stable coalitions. We test this conjecture in the next section.

The second statement relates changes of equilibrium strategies to price effects. If mitigation costs increase uniformly across players, then players will reduce their mitigation levels and increase their adaptation levels.

Thus, without doubt, considering Proposition 2 and 3 together, in our model, adaptation and mitigation are strategic substitutes. The result hinges on the certainly plausible assumption that the cross-derivative B_{Qx} is negative. This would be different for $B_{Qx} > 0$, which, as argued in the introduction, could be possible for some other interesting public-private good problems.

4 First Stage of Coalition Formation

In this section, we analyze stable coalitions. In a first step, we look at the general properties of coalition formation. The purpose is to find out whether the general properties in the M+A-game are fundamentally different from those in the M-game. It will turn out that properties can be established under more general conditions in the M+A-game than in the M-game, there are differences in the two games, but they are not sufficiently pronounced to draw general conclusions about the size and the success of stable coalitions in the two games. Therefore, in a second step, we look at two specific payoff functions, which reveal interesting differences in both games.

4.1 General Properties

Proposition 4 summarizes what we know in terms of mitigation and adaptation levels when the degree of cooperation changes, i.e. the size of coalition P (denoted by p) increases. Note that any discrete change of p (because the number of signatories must be an integer value) is captured by a continuous change and hence we can use the differential with respect to p.

Proposition 4: Equilibrium Mitigation and Adaptation and the Degree of Cooperation

Consider an arbitrary coalition of size p, 1≤p<n, and let $A := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}} >\!<\!= 0$ *in the M+A-game and* $A := B_{QQ} \leq 0$ *in the M-game. Further assume the Additional Assumption to hold in the M+A-game and let an asterisk denote equilibrium values for a given p.*

Mitigation in the M+A-game and M-game

a) Non-signatories:

i) $\frac{dq^*_{j \notin P}(p)}{dp} > 0$ *if and only if A>0;*

ii) $\frac{dQ^*_{j \notin P}(p)}{dp} >\!< 0$ *if A>0 and* $\frac{dQ^*_{j \notin P}(p)}{dp} < 0$ *if A≤0;*

b) Signatories:

i) $\frac{dq^*_{i \in P}(p)}{dp} > 0$ *if A≥0 and* $\frac{dq^*_{i \in P}(p)}{dp} >\!< 0$ *if A<0;*

ii) $\frac{dQ^*_{i \in P}(p)}{dp} > 0$ *;*

c) Aggregate: $\frac{dQ^*(p)}{dp} > 0$.

Adaptation in the M+A-game

d) Signatories and non-signatories: $\frac{dx^*}{dp} < 0$.

Proof: See Working Paper 1.

Generally speaking, the change of equilibrium mitigation levels of signatories and non-signatories (statements a and b) resulting from a change of the coalition size are mostly (though not always) related to the sign of the term A and hence to the sign of the slopes of the reaction functions. Part ai confirms that non-signatories will decrease (increase) mitigation levels when the degree of cooperation increases if reaction functions are downward (upward) sloping. If a non-signatory joins the coalition, the total mitigation level of signatories, $Q_{i \in P}$, increases (Part bii), and the remaining individual non-signatories match this behavior if mitigation levels are strategic complements and undermine this effort if they are substitutes.

Clearly, moving from p to $p+1$, means one non-signatory less and hence if individual non-signatories' equilibrium provision levels $q_{j \notin P}$ drop (or remain constant) as p increases (which happens if *A≤0*), the total provision level of non-signatories, $Q_{j \notin P}$, will drop. However, if mitigation levels are strategic complements, then there are two opposing effects and hence overall predictions are generally not possible (Part aii).

Interestingly, despite signatories' total mitigation level always increases with the degree of cooperation (Part bii), individual mitigation levels do not necessarily have to increase (Part bi). On the one hand, one more member calls for higher individual provision levels because more players internalize the externality among them. On the other hand, before the expansion of the coalition, the new member had lower marginal mitigation costs than the old members; now when joining the coalition, the equalization of marginal mitigation costs (as a result of cost-effectiveness within the coalition) calls for a higher mitigation level of the new member but could call for lower mitigation levels of old members compared to the initial situation provided *A<0*.

At the aggregate things are clear-cut: total mitigation level increases with the size of the coalition (Part c). As total mitigation and adaptation are strategic substitutes, it is not surprising that the opposite holds for adaptation levels (Part d). This suggests that not only in the M-game, total mitigation increases with the degree of cooperation and obtains its highest level in the social optimum, but also in the M+A-game. Because of the substitutional relation between adaptation and mitigation, for any degree of cooperation, total mitigation will be lower in the M+A-game than in the M-game as already observed in Proposition 3. Hence, the main difference between the M+A-game and the M-game relates to the fact that non-signatories may increase their mitigation levels and hence match signatories' behavior if the term A is positive in the M+A-game.

We now conduct a similar analysis in terms of payoffs (see Proposition 5 below) which are ultimately relevant when it comes to evaluate the success of coalition formation (normative dimension) and the incentive to form stable coalitions (positive dimension). The normative dimension relates to cohesiveness and full cohesiveness and the positive dimension to the properties superadditivity and positive externality. Whereas (strict) cohesiveness holds trivially in an externality game, full cohesiveness is much more difficult to establish except if *A≥0*. In the M-game, we know this is only the case if $B_{QQ} = 0$ whereas in the M+A-game this does not constitute a special case. However, in the case of *A<0*, things are less straightforward. The reason is that if mitigation levels are strategic substitutes, an expansion of the coalition means on the one hand higher total mitigation levels but on the other hand an increasing difference between signatories' and non-signatories' mitigation levels and hence an increasing difference in marginal mitigation costs, a source of inefficiency.

Note that $A \geq 0$ is also a sufficient condition for superadditivity to hold, which together with the positive externality property give directly full cohesiveness. Again, superadditivity could fail for some p if $A<0$ as will become apparent from example 2 in Subsection 4.2 (see in particular footnote 11). Typically, this is the case if the absolute value of *A* is large and if p is small because then the leakage effect is particularly strong (i.e. reaction functions are steep and there are many non-signatories, countervailing signatories' efforts to increase mitigation). Clearly, superadditivity cannot be violated over the entire range of p as otherwise cohesiveness could not hold.

Proposition 5: Equilibrium Payoffs and the Degree of Cooperation

Let $A := B_{QQ} + \frac{(B_{xQ})^2}{D_{xx} - B_{xx}} >\!<\!= 0$ *in the M+A-game and* $A := B_{QQ} \leq 0$ *in the M-game. Further assume the Additional Assumption to hold in the M+A-game.*

a) Both games are (strictly) cohesive.

b) In both games the positive externality property (strictly) holds.

c) In both games a sufficient condition for (strict) superadditivity is A≥0 which is also sufficient for (strict) full cohesiveness.

Proof: See Working Paper 1.

There are three conclusions which can be derived from Proposition 5. Firstly, at a general level, the incentive structure to form large stable coalitions does not appear to be fundamentally different in the two games because both exhibit the positive externality property. Secondly, the normative motivation to search for large stable coalition can be established under sufficient conditions which are less restrictive in the M+A-game than in the M-game because $A \geq 0$ does not require linear benefit functions ($B_{QQ} = 0$) in the M+A-game. Thirdly, the same applies to superadditivity, a condition which is crucial for the stability of coalitions. In order to highlight the importance of superadditivity for stability, we provide Proposition 6.

Proposition 6: The Role of Superadditivity for Stable Coalitions

a) A non-trivial stable coalition exists in a game which is superadditive.

b) If a coalition of size p≥2 is internally stable, then the move from p-1 to p is superadditive.

c) If the move from p-1 to p is superadditive, then the payoff of signatories increases through this move.

Proof: See Working Paper 1.

Part a of Proposition 6 is interesting in that it establishes sufficient conditions for the existence of a non-trivial coalition. However, at this level of generality, it is not clear how large stable coalitions will be and whether they are larger in the M+A-game than in the M-game and if so on what this depends. Part b is similar in spirit, looking at superadditivity and internal stability in the neighborhood of a coalition of size p. The problem is that superadditivity is only a necessary condition but not a sufficient condition for internal stability. Part c reminds us that because non-signatories' payoffs increase with the degree of cooperation due to the positive externality property, we need for internal stability that also signatories' payoffs increases in the neighborhood of p for which superadditivity is a sufficient condition. However, even if signatories' payoffs constantly increase in p for all p, it is still difficult to predict stable coalitions. The reason is that starting from $p=1$ in which case $\Pi^*_{i\in P}(1)=\Pi^*_{j\notin P}(1)$, gradually increasing p, we need that $\Pi^*_{i\in P}(p)$ increases faster than $\Pi^*_{j\notin P}(p-1)$ in order to have large internally stable coalitions. The central question is, however, what "faster" means. The answer is not straightforward because $\Pi^*_{i\in P}(p)<\Pi^*_{j\notin P}(p)$ for any p from Lemma 2 and hence the "fast increase" of $\Pi^*_{i\in P}(p)$ must happen within a very short interval to have internal stability at p, i.e. $\Pi^*_{i\in P}(p)\geq\Pi^*_{j\notin P}(p-1)$. Finally, to make things even worse, we cannot rule out the possibility that $\Pi^*_{i\in P}(p)$ decreases first and then increases in p and we still may have a stable coalition at the increasing part of $\Pi^*_{i\in P}(p)$. It is because of this lack of analytical tractability at the general level why all papers which analyzed stable coalitions in the M-game have considered specific payoff functions and often used simulations.

4.2 Examples

We consider two specific payoff functions which we call example 1 and 2. Both examples assume quadratic costs functions. Example 1 assumes a linear benefit function with the following payoff function

(5) $$\Pi^M_{i(1)}=bQ-\frac{c}{2}q_i^2$$

in the M-game and

(6) $$\Pi^{M+A}_{i(1)}=b(1-\gamma x_i)Q+a(1-\lambda Q)x_i-\frac{c}{2}q_i^2-\frac{d}{2}x_i^2$$

in the M+A-game where the parameters *a*, *b*, *c*, *d*, γ and λ are assumed to be strictly positive. In example 1, $A^M=0$ and $A^{M+A}>0$. Example 2 assumes again a linear benefit function in terms of adaptation but a quadratic benefit function in terms of mitigation, such that we have $A^M<0$ and $A^{M+A}><=0$ where the sign of A^{M+A} depends on the parameter values.

(7) $$\Pi^M_{i(2)}=\left(aQ-\frac{b}{2}Q^2\right)-\frac{c}{2}q_i^2$$

(8) $$\Pi^{M+A}_{i(2)}=\left(aQ-\frac{b}{2}Q^2\right)+x_i(e-fQ)-\frac{c}{2}q_i^2-\frac{d}{2}x_i^2$$

Again, we assume all parameters *a*, *b*, *c*, *d*, *e*, and *f* to be strictly positive. For both examples we need to impose conditions such that the examples are in line with the General

Assumptions and that the Additional Assumption in the M+A-game hold. This includes conditions to ensure interior second stage equilibria for every p. Those conditions as well as all subsequent results are spelled out in detail in the Working Paper 1 in Appendix 3. At an analytical level, the following results can be derived.

Proposition 7: Stable Coalitions in Example 1 and 2

Assume the General Assumptions as well as the Additional Assumptions to hold for example 1 and 2.

a) In example 1, $A=0$ *and* $p^*=2$ *and* $p^*=3$ *in the M-game, where the second Pareto-dominates the first equilibrium. In the M+A-game, A>0 and* $p^*\geq 3$.

b) In example 2, A<0 and $p^*=1$ *or* $p^*=2$ *in the M-game. In the M+A-game,* $p^*\geq 3$ *if A≥0.*

Proof: See Working Paper 1.

Both examples confirm the intuition that if reaction functions are upward sloping in the M+A-game, stable coalitions will be (weakly) larger in the M+A-game than in the M-game. However, in order to obtain further conclusions, we need to conduct simulations. For example 1, we would like to find out whether stable coalitions will be strictly larger in the M+A-game than in the M-game. This is simulation run 1. For example 2, we conduct three simulation runs. Simulation runs 2 and 3 assume *A>0* in the M+A-game, illustrating that only if the absolute value of *A* is large enough will stable coalitions be strictly larger than $p^*=3$. Finally, simulation run 4 assumes *A<0* in the M+A-game, like in the M-game, illustrating that then stable coalitions can even be smaller in the M+A-game than in the M-game.[19, 20] Apart from determing stable coalitions, the simulation runs allow us to draw interesting conclusions regarding global mitigation levels and payoffs.

The main results are displayed in Table 1 to 4. The legend describes the range of parameters considered in the simulation runs. Simulation set 1 lists the total number of simulations and set 2 the number of valid runs, i.e. those simulations which observe the conditions listed in Appendix 3. If different stable coalitions emerge, set 2 is grouped according to the size of stable coalitions. For instance, in Table 1, set 2 contains 2620 simulations of which 2616 deliver a stable coalition of size 3 and 4 simulations deliver a stable coalition of size 10 in the M+A-game, which is the grand coalition in the example because $n=10$. (All 2620 simulations deliver a coalition of size 3 in the M-game, as predicted by Proposition 7.) The average coalition size over all 2620 simulations is denoted by an upper bar in the last column. Generally, upper bars denote averages over valid simulation runs.

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19 For simulation run 4, the term A in the M+A-game is always smaller in absolute terms than in the M-game but coalitions can be smaller. This stresses that the intuition a less negatively sloped reaction function leads to larger coalitions is wrong. It also highlights the need for simulations.

20 Since $p^*=1$ for some parameter values in the M+A-game in simulation run 4, superadditivity must fail when forming a two player coalition. Note that this does not contradict Proposition 5, which establishes superadditivity for *A≥0*.

The interpretation of $\overline{A}$, $\overline{Q}^*(p^*)$ and $\overline{x}^*(p^*)$ are obvious where the latter two being the averages in stable coalitions of size p^*. $\overline{I}^{SO}(\overline{I}^{CO})$ is the average of index $I^{SO}=\frac{\Pi^{*SO}}{\Pi^{*NE}}$ $\left(I^{CO}=\frac{\Pi^{*CO}}{\Pi^{*NE}}\right)$, a relative welfare measure, with Π^{*SO}, Π^{*CO} and Π^{*NE} denoting the total payoff in the social optimum, equilibrium coalition and the Nash equilibrium, with the superscripts *SO*, *CO* and *NE*, respectively, where the first two coincide if $p^*=n$ and the last two coincide if $p^*=1$. The larger I^{SO}, the larger the difference between the social optimum and the Nash equilibrium in relative terms and hence the larger is the need for cooperation. Index I^{CO} measures the success of stable coalitions in relative terms, also relating it to the Nash equilibrium. The following comments and conclusions apply to all four simulation runs.

Firstly note that for a given p, Q^* is lower in the M+A-game than in the M-game because adaptation is available as a second strategy as we know from the previous theoretical analysis (Proposition 3). Of course, if stable coalitions are larger in the M+A-game than in the M-game, then $Q^*(p^{*M+A})>Q^*(p^{*M})$ is possible and the same applies to averages (e.g. Simulation run 1: $\overline{Q}^*(p^{*M+A}=10)>\overline{Q}^*(p^{*M}=3)$ and Simulation run 3: $\overline{Q}^*(p^{*M+A}=10)>\overline{Q}^*(p^{*M}=2)$). However, in terms of overall averages, in the examples, even in simulation runs 1 and 3, $\overline{Q}^*(\overline{p}^{*M+A})<\overline{Q}^*(\overline{p}^{*M})$ because the average coalition sizes over all simulations is not sufficiently larger in the M+A-game compared to the M-game (simulation runs 1, 2 and 3) and may even be smaller as in simulation run 4.

Secondly, in absolute terms, global welfare in the social optimum, stable coalitions and Nash equilibrium is higher in the M+A-game than in the M-game.[21] This does not only hold for averages as displayed in the tables but holds for every simulation run. Regarding the social optimum, this is obvious because in the absence of any strategic interaction, having more strategies available in the M+A-game than in the M-game must lead to a higher global payoff. More remarkable is that this also holds in the Nash equilibrium and even for stable coalitions in simulation run 4 for those parameter values where stable coalitions in the M+A-game are smaller than in the M-game. Even though adaptation helps to reduce the costs to address climate change, mutual positive externalities across players are generated through mitigation, which is higher in the M-game than in the M+A-game for every coalition *p*, *1≤p≤n* as stated in Proposition 3. So the cost effect appears to be stronger than the externality effect in our example.

Thirdly, the ratio of aggregate payoffs in the M+A and M-game decreases when going from the Nash equilibrium to stable coalitions and finally to the social optimum in which this ratio is close to 1. This suggest that adaptation as an additional strategy is particular useful if there is no cooperation, but its value decreases with the degree of cooperation. The intuition is that cooperation is about coordinating mitigation levels across players, and hence the value of adaptation decreases with the degree of cooperation.

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21 Generally speaking, welfare comparisons between the two games are not valid. They are valid for our two examples because by design $\Pi_i^{M+A}(x_i=0)=\Pi_i^M$.

Fourthly, and reiterating the last point, the indexes I^{SO} and I^{CO} are smaller in the M+A-game than in the M-game, and this applies not only to averages as displayed in the tables, but is also true for every individual simulation. For the index I^{CO} this is even true for those cases where the grand coalition forms in the M+A-game whereas a much smaller coalition emerges in the M-game (simulation runs 1 and 3). Thus, in relative terms the need for cooperation, measured by I^{SO} and the success of cooperation, measured by I^{CO}, are lower in the M+A-game than in the M-game.

The overall message is clear: under those conditions when reaction functions are upward sloping in the M+A-game, stable coalitions as well as total welfare may be larger in the M+A-game than in the M-game, and even total public good provision levels may be larger despite adaptation if the stable coalition size is much larger in the M+A-game than in the M-game. However, the importance of adaptation decreases with the degree of cooperation and the relative gains from forming stable agreements may well be smaller in the M+A-game than in the M-game.

5 Summary and Policy Conclusions

In this report, we have analyzed how adaptation, as an additional strategy to mitigation, affects the prospects of international policy coordination to tackle climate change. More specifically, we have studied the strategic interaction between mitigation and adaptation strategies in the canonical model of international environmental agreements (IEAs). Our key research question was: how does adaptation, as an additional strategy to mitigation, affect the prospects of international policy coordination to tackle climate change? However, in our analysis, we answered many more questions which we discuss below.

Are mitigation and adaptation strategic substitutes or complements?

This question has also been addressed by Ingham et al (2005) and Tulkens and van Steenberghe (2009), though not in the context of treaty formation. As Ingham et al. (2005) point out, to answer this question requires a clear definition of substitutability and complementarity. We have considered various definitions, which all come to the same conclusion, namely that adaptation and mitigation are substitutes. They are only complements when using loose language by meaning that they both “complement each other in addressing the problem of climate change”. We showed that by changing the level of mitigation in a ceteris paribus manner, an increase of mitigation calls for a reduction of adaptation as an optimal response in equilibrium. Also whenever adaptation is available, the optimal level of mitigation will be lower than if this option is not available. Irrespective of the level of cooperation, we showed that the optimal mix to address the climate change problem uses both strategies and this means a lower level of mitigation if adaptation is available. Also increasing the cost of mitigation will lower the equilibrium mitigation level and most importantly will increase the level of adaptation. And of course the reverse is also true: increasing the cost of adaptation will lower the level of adaptation but will increase the use of mitigation to address the climate change problem. The latter interpretation is in line with the classical definition in microeconomics. Our conclusion is also in line with Ingham et al (2005).

How does adaptation and mitigation change with the degree of cooperation?

In a setting where only mitigation is available to tackle climate change, the total level of mitigation increases with the degree of cooperation. That is, the more countries join a climate treaty, the larger will be the total level of mitigation. A treaty which comprises all countries is socially optimum. The difference between no and full cooperation increases with the benefit-cost ratio from mitigation. That is, the larger the benefits from mitigation compared to the costs, the larger will be the difference between full and no cooperation, i.e. the larger is the degree of externality and they need for cooperation. This difference in total mitigation levels also shows up in the difference in global welfare between full and no cooperation. In climate change, and following the latest IPCC report, it is expected that the benefits from mitigation are large compared to the costs of addressing the climate change problem.

Including the possibility of adaptation does not change this conclusion fundamentally, but there are differences. Firstly, total mitigation levels will also increase with the degree of cooperation and will be highest under full cooperation. However, for any given degree of cooperation, the total level of mitigation will be lower. This is because in an optimal policy mix, adaptation will be used to tackle climate change and both strategies are substitutes. Secondly, the level of adaptation decreases with the level of cooperation. Cooperation is about coordinating strategies which are beneficial to all countries. This is true for mitigation, which is a public good, but is not true for adaptation, which is a private good. Our simulations showed that adaptation is an important part in the policy mix if there is no coordinate climate policy, but is far less important if there is a substantial degree of cooperation. This also means that the welfare gain from using adaptation in addition to mitigations is much higher if there is no or hardly any cooperation on addressing the climate change problem than if there is substantial amount of cooperation. Given the lack of effective cooperation on climate change over the last 25 years or so suggests that adaptation may be viewed as a sensible second-best policy option. Moreover, being critical about the prospects of effectively addressing climate change in the near future despite the Paris Accord in 2015, and signed recently, it would not be economically irrational to use adaptation apart from mitigation in an optimal policy mix. In any case, irrespective of the degree of cooperation, all our simulations showed that total welfare is higher with than without adaptation, though this difference decreases with the degree of cooperation. Nevertheless, our simulations in section 4.2 clearly showed that for the normative benchmark of a first-best solution, adaptation is of minor importance.

How does adaptation changes the incentives in climate change?

Mitigation is a pure public good associated with the problem of free-riding, which has also been called easy-riding. The reason is simple. No country can be excluded to enjoy the benefits from mitigation. This creates a kind of prisoners' dilemma kind of situation: countries would be better off by moving from no cooperation to full cooperation, but they are even better off if others cooperate and they free-ride. The reduction in total mitigation is marginal but the reduction in mitigation cost is substantially. That is, self-fish and/or rational behaviour defined in a narrow sense explain the lack of sufficient international cooperation on climate change. That is, individual and global rationality are different. We referred to this as the paradox of cooperation in the introduction to this report. The main issue which we tried to address in this report is whether this incentive structure will change in the light of adaptation. The answer has several aspects.

Firstly, adaptation reduces the cost of addressing the problem of climate change. Secondly, in equilibrium, the level of mitigation is lower, which, ceteris paribus causes less of free-riding. In some sense, the need for cooperation is reduced and hence more manageable. Thirdly, the very fundamental incentive to form agreements does not change. Those that remain outside an agreement are still enjoying the non-exclusive benefits whenever the degree of cooperation increases. But those non-exclusive benefits are smaller if adaptation is a second strategy besides mitigation. Fourthly, if there are strong cross effects between mitigation and adaptation, mitigation levels can become strategic complements. That is, the cooperative efforts of the members of a climate treaty are no longer undermined by non-signatories via carbon leakage. To the contrary, in these cases non-signatories also increase their mitigation efforts, matching the behaviour of signatories. Our simulations showed that even the grand coalition, i.e. an agreement including all countries could be stable. Fifthly, irrespective whether stable treaties are larger with adaptation than without, all our simulation runs showed that global welfare in equilibrium (i.e. stable agreements) is larger by a factor between 2 and 5 if adaptation is used as an additional strategy to mitigation. Of course, those numbers are derived from a stylized model and the absolute difference is not important as such. Nevertheless, given the larger number of simulations which we ran, there is a clear indication that adaptation will foster the prospects of cooperation in the light of strong free-rider incentives which may be associated with substantial gains from cooperation. In order to determine the absolute magnitude if would be interested to run those simulations for a calibrated climate model, like CLIMNEG (Carraro et al. 2006 and Eyckmans and Finus 2009), STACO (Finus 2008, Finus et al. 2006) and WITCH (Bosello et al. 2003 and Buchner and Carraro 2007). We need to leave this for future research.

What are the conditions that adaptation causes mitigation levels to be strategic complements?

In the technical part of this report, we showed that mitigation level in different countries can become strategic complements if term A is positive and this facilitates larger stable climate agreements. Though it is not straightforward to interpret this term, we would like to provide some hints. See also Ebert and Welsch (2011). When looking at the difference components of term A, we can drawn the following conclusion. Term increases, ceteris paribus, if

a) the marginal cost functions of adaptation are relatively flat

b) the marginal benefits of adaptation do not decrease much

c) the cross effects on the benefit side between adaptation and mitigation are large.

d) the marginal benefits of mitigation do not decrease much

a) implies that the additional cost of adaptation when using more adaptation does not increase sharply but only modestly. b) implies that even for high levels of adaptation the additional benefit from adaptation does not decrease a lot. a) and b) together may be interpreted such that adaptation is an effective measure to address the climate change problem. c) means that mitigation and adaptation are good substitutes for addressing the climate problem. In other words, climate change damages cannot only be reduced by mitigation but adaptation does a similar job. d) means that that even for high levels of mitigation the additional benefit from mitigation does not decrease a lot. Of course, the question to which extent this conditions hold is an empirical question. However, given the relative low current levels of mitigation as well as adaptation suggests that it is not unlikely that these conditions hold. This would also be in line with the observation that the recent Paris Accord was signed by many more countries than the previous Kyoto Protocol as the role of adaptation has become much more prominent over time. Recalling the conclusions from above, and the discussion in the introduction related to optimist versus pessimists, overall there seems a clear indication that including adaptation in the portfolio of strategies to address the climate change problem mitigates the free-rider incentive and is associated with higher global welfare. This is at least true for the current low levels of cooperation and coordination at an international scale. In the long-term adaptation may become less important, but only provided the level of cooperation and coordination increases substantially and at a large scale.

What are the limitations of our analysis?

Our model made a couple of assumptions in order to capture the main driving forces analytically. For instance, we considered one of the most widespread coalition games and stability concepts (internal and external stability in a cartel formation game) but could have considered other concepts (Bloch 1997, Finus and Rundshagen 2009 and Yi 1997). Internal and external stability implies that after a player leaves the coalition, the remaining coalition members remain in the coalition. In the context of a positive externality game, this is the weakest possible punishment after a deviation and hence implies the most pessimistic assumption about stability. This appears to be a good benchmark because we could show that with adaptation larger coalitions can be stable, including the grand coalition. What would certainly be interesting is to depart from the assumption of symmetric players in order to capture better the current discussion whether industrialized countries should support developing countries not only in their mitigation but also their adaptation efforts (Lazkano et al. (2016)) Will support in adaptation buy more mitigation? In this context one could assume that coalition members can pool their adaptation activities as a club, deriving an additional benefit compared to non-signatories from the cost-effective production of adaptation. Essentially, this would require to model in kind-transfers apart from monetary transfers in a coalition formation model with heterogeneous agents. We will comment on this issue as well as some further issues in section 6.

6 Further Policy Issues

Dynamic Payoff Structure

Combining the analysis of agreement formation with a dynamic payoff structure, in order to account for the fact that greenhouse gases are a stock and not a flow pollutant has been considered in empirically calibrated climate models for instance by Bosello et al. (2003) and Eyckmans and Finus (2009) and in a theoretical model Rubio and Casino (2005) in the context of mitigation. Essentially, the decision whether to join a treaty or remain outside is based on the net present value of a future payoff stream. The basic incentive structure to join agreements which we described in section 2.2 with various properties (e.g. cohesiveness, superadditivity and positive externalities) does not really change when considering a dynamic payoff structure. Consequently, the main conclusion summarized in the paradox of cooperation is also valid for a dynamic payoff structure. Also our conclusion that total mitigation increases and adaptation decreases with the degree of cooperation would most likely hold, as it is suggested by Bréchet (2013 and 2016). At least they show that the social planner would uses less adaptation and more mitigation than if there is no cooperation. One can also suspect that an optimal time path would delay adaptation, assuming that adaptation cost decline in the future due to technological innovation. Moreover, the benefit of adaptation increases with level of greenhouse gas concentration which will be higher in the future. Clearly, the lower the discount rate by which the future is discounted and the lower the natural decay of greenhouse gases, the higher will be the benefits of mitigation, anything else being equal (Bosello et al. 2014). Thus, in the light of possible funding constraints, in the short-run, the focus should be on mitigation whereas in the long-run adaptation may become more important in the optimal policy mix. In particular, in the light of uncertainties surrounding the benefits and costs of mitigation and adaptation, a delay of adaptation actions (in relation to mitigation) seems sensible.

Timing of Adaptation and Mitigation

In this report, we considered two versions in terms of the timing. Version 1: mitigation and adaptation are chosen simultaneously. Version 2: countries chose first mitigation and then adaptation. We showed that both versions are equivalent. One may argue that version 2 is in line how the discussion in climate change has evolved over time. Version 3, which reverses the sequence between mitigation and adaptation compared to version 2, appeared to us only as theoretical possibility. However, Heuson et al. (2015) argue that the current climate negotiations could be interpreted as version 3. That is, countries have shifted their focus on adaptation, invest in adaptation, and negotiate about mitigation with a long-term view. Version 3 has already been considered by Zehaie (2009) for two players. He showed that players choose strategically high levels of adaptation as a kind commitment device which makes it credible to argue that they are not much interested in mitigation. In other words, the free-rider incentive resulting from the strategic interaction of mitigation levels in different countries would be reinforced through adaptation. This basic negative message is reiterated by Heuson et al. (2015) which add an investment stage to their model. Investment concerns R&D in the development of efficient mitigation technology. Such an investment stage precedes mitigation. Governments or firms strategically underinvest in R&D in order to mitigate less later on as mitigation is costly. This problem is discussed in the literature as the hold-up problem. Essentially, adaptation before mitigation does a similar job: high adaptation levels signal a low preference for mitigation as adaptation ensures against high climate damages. In order to avoid such negative strategic effects, it is of great importance to discuss issues of sharing R&D-investments, technological transfers, adaptation and mitigation as a package in any future climate negotiations. The Paris Accord has done exactly this and included all these aspects in the treaty and hence should be judged positively.

Asymmetry

Even though our assumption about the symmetry of countries in our stylized model appears to be restrictive, we have not indication that the fundamental conclusions derived would change as emerges from Eisenack and Kaehler (2016) and Lazkano, et al. (2016). The conclusion that adaptation can lead to larger stable climate agreements with larger global welfare gains would still hold. In order to internalize those gains, most likely, monetary transfer or in-kind transfers would be necessary to balance a possible unequal distribution of those gains. With those compensation mechanisms asymmetry could even foster cooperation and even more optimistic results could be obtained. This issue is discussed below.

Climate Finance

The possibility to use transfers, monetary or in-kind transfers to enlarge environmental treaties and to increase their effectiveness has been debated and analysed for a long time. In a recent and seminal paper, Finus and McGinty (2015) show that in the context of mitigation, transfers can stabilize large agreements, including the grand coalition. The show that asymmetry may in fact be an asset and not an obstacle for cooperation. Asymmetry allows to exploit comparative advantages among signatories, and these advantages are exclusive to signatories and increase with diversity. This asymmetry becomes a push and not pull factor for cooperation. Of course, those differences require a compensation mechanism such that the gains from cooperation are shared equally. The central question is whether adaptation would change this major insight. It seems not. However, with adaptation there could be a second option, namely in kind-transfers. Sharing adaptation technology and/or producing adaptation jointly in the light of different adaptation costs, could provide some additional leverage to foster cooperation. Intuition would suggest that if we allowed in our model for different adaptation cost, then signatories, by pooling their adaptation efforts, could gain an additional advantage, despite adaptation is a private and not a public good. Moreover, one could imagine that adaptation and mitigation are linked through a conditionality clause as suggested by Bosello et al. (2014). Developing countries receive monetary or in-kind transfer to build up adaptation capacity if and only if they commit to increase their mitigation efforts. This could provide a push for cooperation on climate change. However, as Bosello et al. (2014) point out, without such a conditionality clause, foreign adaptation aid just replaces domestic investment and may even decrease mitigation efforts by developing countries. The latter being the case because adaptation reduces the pressure to deal with climate change damages through mitigation. It is thus important to avoid such crowding-out effects by linking both strategies in negotiations. Of course, this ignores any ethical issues which may call to support developing countries regarding adaptation because they are the most vulnerable countries, irrespective whether this benefits developing countries. However, in a strategic context it is evident that without linking support of adaptation in developing countries to mitigation efforts, industrialized countries have little incentive to do so. See Buob and Stephan (2013) and Heuson et al. (2014) for a further discussion of this issue.

Uncertainty and Risk

There is quite some literature which looks at how uncertainty about the benefits and costs of mitigation impact on the prospects of treaty formation. The first papers assumed risk neutrality and came to the counter-intuitive conclusion that "learning can be bad" for the success of coalition formation (Kolstad 2007, Kolstad and Ulph 2008, Na and Shin 1998 and Ulph 1998). Even Kolstad and Ulph (2011) came to a similar negative conclusion. In contrast, Dellink and Finus (2012) in a calibrated climate simulation model and Finus and Pintassilgo (2012 and 2013) in stylized theoretical model substantially qualified this conclusion. In particular in Finus and Pintassilgo (2012 and 2013) it is systematically shown that the result is an artefact of a too simple model and that those counter-intuitive results only hold for very special assumptions. For instance, if there is pure uncertainty about the distribution of the benefits from mitigation, then learning can indeed lead to only small treaties being stable. The reason is that the veil of ignorance (no learning) allows all countries to expect more or less the same gains from cooperation whereas under learning the possible losers are identifiable. However, Finus and Pintassilgo (2012 and 2013) show that by using a transfer scheme through which those that gain more than proportional compensate those that may lose, the problem can be fixed. Once the distributional issue is fixed, the benefits of better targeting mitigation efforts with more information prevail, i.e. learning becomes beneficial.

Also risk aversion tends to improve upon the cooperative outcome. If governments are risk-averse, there is a premium to hedge against this risk via cooperation (Boucher and Bramoullé 2010, Bramoullé and Treich 2009 and Finus et al. 2014). That is, the more risk-averse governments are, the more they will mitigate and the larger is the participation in treaties.

The question is whether adaptation would change the major insights regarding uncertainty and risk derived for a pure mitigation game. Of course without developing such a model we can only propose some conjectures. Essentially, adaptation, like mitigation allows to hedge against risk, and one would assume that the equilibrium level of both strategies increase with the degree of risk aversion (see Markandya 2016 et al.). A priori we cannot see any reason why the “positive effect“ of adaptation on the success of cooperation should disappear in a setting with uncertainty and/or risk.

Tipping Points

Barrett (2013) has analysed how the possibility of catastrophic events will change the incentive structure of international treaty formation to address climate change. He ignores adaptation and assumes that damages from emissions are no longer continuous, but that if the greenhouse concentration reaches a certain threshold, also called tipping point, the damage function kinks, and damages become suddenly very large if not infinite. That is, above the tipping point the climate system collapses. He first assumes that the tipping point is known. He shows that the threat of very large damages once the threshold is surpassed fosters cooperation. Essentially, the threat transforms the prisoners’ dilemma into an assurance game, which only requires that governments coordinate on the good equilibrium. Essentially, the discontinuity of damages translates into a discontinuity of membership decisions, like a minimum participation clause (Carraro et al. 2009). At the tipping point, one country leaving the agreement would have severe consequences, which works like a deterrent. Then Barrett assume that damages once the tipping point has been passed are uncertain. He shows that this will not change the incentive structure as long as the expected damage is large enough and functions like a deterrent. Finally, he shows that if the threat point is uncertain, then we are back in a prisoners’ dilemma game. The reason is that uncertain about the location of the tipping point makes the kink in the damage function to disappear and the expected damage function is smooth and continues. Interesting enough, Tavoni et al. (2011) confirm those conclusion in an experiment.

The question arises what would change if adaptation is added to mitigation in the set of strategies to address climate change. It appears that adaptation can neither increase nor decrease the uncertainty where the tipping point is located. It seems also unlikely that adaptation can make the tipping point to disappear. Moreover, it seems rather implausible that adaptation would reduce the expected damage once the threshold is reached. Only the expected damage up to the point of the threshold would be reduced through adaptation which implies that the positive effect of the fear not to pass the tipping point of the climate system on the degree of cooperation will not go away with adaptation. Thus, if the threat to pass a tipping point leads to full cooperation, then of course and as pointed out above, the gains from adaptation are rather marginal. Only through mitigation can a catastrophic event be avoided, which devalues the role of adaptation (Bosello et al. 2014).

6 References

[1]. d'Aspremont, C., A. Jacquemin, J.J. Gabszewicz and J.A. Weymark (1983), On the Stability of Collusive Price Leadership. "Canadian Journal of Economics", vol. 16(1), pp. 17-25.

[2]. Barrett, S. (1994), Self-enforcing International Environmental Agreements. "Oxford Economic Papers", vol. 46, pp. 878-894.

[3]. Barrett, S. (2002), Consensus Treaties. "Journal of Institutional and Theoretical Economics", vol. 158(4), pp. 529-547.

[4]. Barrett, S. (2003), Environment and Statecraft: The Strategy of Environmental Treaty-making. Oxford University Press, New York.

[5]. Barrett, S. (2006), Climate Treaties and "Breakthrough" Technologies. "American Economic Review", vol. 96(2), pp. 22-25.

[6]. Barrett, S. (2008), Dikes vs. Windmills: Climate Treaties and Adaptation. Johns Hopkins University, School of Advanced International Studies.

[7]. Battaglini, M. and B. Harstad. (2016). Participation and Duration of Environmental Agreements. Journal of Political Economy, forthcoming.

[8]. Baumol W.J. and D.F Bradford. (1972), Detrimental Externalities and Non-Convexity of the Production Set. "Economica", vol. 39, pp. 160-76.

[9]. Benchekroun, H., Marrouch, W. and A.R. Chaudhuri. (2016), Adaptation Technology and Free-riding Incentives in International Environmental Agreements, in Economics of International Environmental Agreements: A Critical Approach. Routledge, UK, forthcoming.

[10]. Benchekroun, H. and F. Taherkhani (2014), Adaptation and the Allocation of Pollution Reduction Costs. “Dynamic Games”, vol. 4, pp. 32-57.

[11]. Bergstrom T. C. and R. P.Goodman (1973), Private Demands for Public Goods. "American Economic Review", vol. 63(3), pp. 280--296.

[12]. Bergstrom, T., L. Blume, and H. Varian. (1986), On the Private Provision of Public Goods. "Journal of Public Economics", vol. 29.1, pp. 25-49.

[13]. Bloch, F. (2003), Non-cooperative Models of Coalition Formation in Games with Spillovers. In: Carraro, C. (ed.), The Endogenous Formation of Economic Coalitions. Edward Elgar, Cheltenham, UK et al., ch. 2, pp. 35-79.

[14]. Boercherding T. E. and R. T.Deacon (1972), The Demand for the Services of Non-federal Governments, "American Economic Review", vol. 62, 891--901.

[15]. Bosello, F., B. Buchner and C. Carraro (2003), Equity, Development, and Climate Change Control. “Journal of the European Economic Association”, vol. 1(2-3), pp. 601-611.

[16]. Francesco Bosello, Enrica De Cian, Licia Ferranna, (2014), Catastrophic Risk, Precautionary Abatement, and Adaptation Transfers, FEEM: http://www.feem.it/getpage.aspx?id=7160&sez=Publications&padre=73

[17]. Boucher, V. and Y. Bramoullé (2010), Providing Global Public Goods under Uncertainty. “Journal of Public Economics”, vol. 94, pp. 591-603.

[18]. Bramoullé, Y. and Treich, N. (2009) Can uncertainty alleviate the commons problem? Journal of the European Economic Association, 7, 1042-67.

[19]. Bréchet, T., N. Hritonenko and Y. Yatsenko (2013), Adaptation and Mitigation in Long-term Climate Policy. “Environmental Resource Economics”, vol. 55, pp. 217-243.

[20]. Bréchet, T., N. Hritonenko and Y. Yatsenko (2016), Domestic Environmental Policy and International Cooperation for Global Commons. “Resource and Energy Economics”, vol. 44, pp. 183-205.

[21]. Buchner, B. and C. Carraro (2007), Regional and Sub-global Climate Blocs. A Cost-Benefit Analysis of Bottom-up Climate Regimes. In Carraro, C. and C. Egenhofer (eds.), Climate and Trade Policy. Bottom-up Approaches Towards Global Agreement. Edward Elgar, Cheltenham, UK et al., ch. 2, pp. 16-41.

[22]. Buob, S. and G. Stephan (2011), To Mitigate or to Adapt: How to Confront Global Climate Change. "European Journal of Political Economy", vol. 27, pp. 1--16.

[23]. Buob, S. and G. Stephan (2013), On the Incentive Compatibility of Funding Adaptation. “Climate Change Economics”, vol. 4(2), pp. 1-18.

[24]. Carraro, C., J. Eyckmans and M. Finus (2006), Optimal Transfers and Participation Decisions in International Environmental Agreements. “Review of International Organizations”, vol. 1(4), pp. 379-396.

[25]. Carraro, C., C. Marchiori and S. Oreffice (2009), Endogenous Minimum Participation in International Environmental Treaties. “Environmental and Resource Economics”, vol. 42(3), pp. 411–425.

[26]. Carraro, C. and D. Siniscalco (1993), Strategies for the International Protection of the Environment. "Journal of Public Economics", vol. 52(3), pp. 309-328.

[27]. Cornes, R., and T. Sandler (1984). Easy Riders, Joint Production, and Public Goods. "The Economic Journal", vol. 94.375, pp. 580-598.

[28]. Cornes, R. and T. Sandler. (1986), The Theory of Externalities, Public Goods and Club Goods. Cambrige University Press.

[29]. Cornes, R. and T. Sandler (1994), The Comparative Static Properties of the Impure Public Good Model. "Journal of Public Economics", vol. 54(3), pp.403-421.

[30]. Cornes, R.C. and R. Hartley (2007), Aggregative Public Good Games. "Journal of Public Economic Theory", vol. 9(2), pp. 201--219.

[31]. Dellink, R. and M. Finus (2012), Uncertainty and Climate Treaties: Does Ignorance Pay? “Resource and Energy Economics”, vol. 34(4), pp. 565-584.

[32]. Deneckere, R. and C. Davidson (1985), Incentives to Form Coalitions with Bertrand Competition. "The RAND Journal of Economics", vol. 16(4), pp. 473-486.

[33]. Donsimoni, M.-P., N.S. Economides and H.M. Polemarchakis (1986), Stable Cartels. "International Economic Review", vol. 27(2), pp. 317-327.

[34]. Ebert, U. and H. Welsch (2011), Optimal Response Functions in Global Pollution Problems Can Be Upward-sloping: Accounting for Adaptation. "Environmental Economics and Policy Studies", vol. 13(2), pp. 129-138.

[35]. Ebert, U. and H. Welsch (2012), Adaptation and Mitigation in Global Pollution Problems: Economic Impacts of Productivity, Sensitivity, and Adaptive Capacity. "Environmental and Resource Economics", vol. 52, pp. 49-64.Eisenack, K., and L. Kähler. (2016), Adaptation to Climate Change Can Support Unilateral Emission Reductions. "Oxford Economic Papers", vol; 68(1), pp. 258-278.

[36]. Eisenack, K. and L. Kaehler (2016), Adaptation to Climate Change Can Support Unilateral Emission Reductions. “Oxford Economic Papers”, vol. 68(1), pp. 258-278.

[37]. El-Sayed, A. and S. Rubio (2014), Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change, "Resource and Energy Economics", vol.38, pp. 168-180.

[38]. Eyckmans, J. and M. Finus (2009), Transfer Schemes and Institutional Changes for Sustainable Global Climate Treaties. In: Guesnerie, R. and H. Tulkens (eds.), The Design of Climate Policy. MIT Press, Cambridge, MA, pp. 103-135.

[39]. Finus, M. (2008), Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks and Future Challenges. “International Review of Environmental and Resource Economics”, vol. 2(1), pp. 29-67.

[40]. Finus, M. and A. Caparrós (2015), Game Theory and International Environmental Cooperation: Essential Readings. Edward Elgar, Cheltenham.

[41]. Finus, M. and S. Maus (2008), Modesty May Pay! "Journal of Public Economic Theory", vol. 10(5), pp. 801-826.

[42]. Finus, M. and M. McGinty (2015), The Anti-Paradox of Cooperation: Diversity Pays (with Matt McGinty). Bath Discussion Paper Series, 40/2015.

[43]. Finus, M. and P. Pintassilgo (2012), International Environmental Agreements under Uncertainty: Does the Veil of Uncertainty Help? “Oxford Economic Papers”, vol. 64, pp. 736-764.

[44]. Finus, M. and P. Pintassilgo (2013), The Role of Uncertainty and Learning for the Success of International Climate Agreements. “Journal of Public Economics”, vol. 103, pp. 29-43.

[45]. Finus, M., P. Pintassilgo and A. Ulph (2014), International Environmental Agreements with Uncertainty, Learning and Risk Aversion. CESIFO WORKING PAPER NO. 4589 CATEGORY 9: RESOURCE AND ENVIRONMENT ECONOMICS.

[46]. Finus, M. and B. Rundshagen (2009), Membership Rules and Stability of Coalition Structures in Positive Externality Games. "Social Choice and Welfare", vol. 32, pp. 389-406.

[47]. Finus, M. and D.T.G. Rübbelke (2013), Public Good Provision and Ancillary Benefits: The Case of Climate Agreements. "Environmental and Resource Economics", vol. 56, pp. 211-222.

[48]. Finus, M., E.C. van Ierland and R. Dellink (2006), Stability of Climate Coalitions in a Cartel Formation Game. “Economics of Governance”, vol. 7(3), pp. 271-291.

[49]. Fraser, C.D. (1992), The Uniqueness of Nash Equilibrium in the Private Provision of Public Goods: an Alternative Proof. "Journal of Public Economics", vol. 49, pp. 389--390.

[50]. Gollier, C. and N. Treich (2003), Decision-making under Scientific Uncertainty: The Economics of the Precautionary Principle. “Journal of Risk and Uncertainty”, vol. 27(1), pp. 77-103.

[51]. Haeringer, G. (2004), Equilibrium Binding Agreements: A Comment. "Journal of Economic Theory", vol. 117(1), pp. 140-143.

[52]. Harstad, B. (2012), Climate contracts: A Game of Emissions, Investments, Negotiations, and Renegotiations. "The Review of Economic Studies", vol. 79(4), pp. 1527-1557.

[53]. Heugues, M. (2014), International Environmental Cooperation: a New Eye on the Greenhouse Gas Emissions' Control. "Annals of Operations Research", vol. 220, pp. 239-262.

[54]. Heusen, C., W. Peters, R. Schwarze and A.-K. Topp (2015), Voluntary International Climate Finance under the Post-Kyoto Framework: the Strategic Consequences of Different Modes of Funding. “Climate Change Economics”, vol. 6(3), pp. 1-27.

[55]. Hirshleifer, J. (1983), From Weakest-Link to Best-Shot: The Voluntary Provision of Public Goods. Public Choice, vol. 41, pp. 371-386.

[56]. Hoel, M. and A. de Zeeuw (2010), Can a Focus on Breakthrough Technologies Improve the Performance of International Environmental Agreements? "Environmental and Resource Economics", vol. 47, pp. 395-406.

[57]. Hof, A., P. Boot, D. van Vuuren, and J. van Minnen (2014), Costs and benefits of climate change adaptation and mitigation: An assessment on different regional scales. The Hague, PBL Netherlands Environmental Assessment Agency.

[58]. Ingham, A., J. Ma and A. Ulph (2005), Can Adaptation and Mitigation be Complements?. Tyndall Centre for Climate Change Research Working Paper 79.

[59]. Kolstad, C.D. (2007), Systematic Uncertainty in Self-enforcing International Environmental Agreements. "Journal of Environmental Economics and Management", vol. 53(1), pp. 68-79.

[60]. Kolstad, C.D. and A. Ulph (2008), Learning and International Environmental Agreements. “Climatic Change”, vol. 89(1-2), pp. 125-141.

[61]. Kolstad, C.D. and A. Ulph (2011), Uncertainty, Learning and Heterogeneity in International Environmental Agreements. “Environmental and Resource Economics”, vol. 50, pp. 389-403.

[62]. Na, S.-L. and H.S. Shin (1998), International Environmental Agreements under Uncertainty. “Oxford Economic Papers”, vol. 50(2), pp. 173-185.

[63]. Laffont, J-J. (1976), Decentralization with Externalities. "European Economic Review", vol. 7, pp. 359-75.

[64]. Lazkano, I., W. Marrouch, B. Nkuiya (2016), Adaptation to Climate Change: How does Heterogeneity in Adaptation Costs Affect Climate Coalitions? "Environment and Development Economics", forthcoming.

[65]. Anil Markandya, Enrica De Cian, Laurent Drouet, Josué M. Polanco-Martìnez, Francesco Bosello (2016), Building Uncertainty into the Adaptation Cost Estimation in Integrated Assessment Models, FEEM: Discussion Paper.

[66]. Poyago-Theotoky, J. (1995), Equilibrium and Optimal Size of A Research Joint Venture in an Oligopoly with Spillovers. "The Journal of Industrial Economics", vol. 43(2), pp 209-226.

[67]. Rubio, S.J. and B. Casino (2005), Self-enforcing International Environmental Agreements with a Stock Pollutant. "Spanish Economic Review", vol. 7(2), pp. 89-109.

[68]. Rubio, S.J. and A. Ulph (2006), Self-enforcing International Environmental Agreements Revisited. "Oxford Economic Papers", vol. 58(2), pp. 233-263.

[69]. Selden, T. and D. Song (1994), Environmental Quality and Development: is there a Kuznets Curve for Air Pollution Emissions?. "Journal of Environmental Economics and Management", vol. (27), pp. 147-162.

[70]. Starrett, D.A. (1972), Fundamental Nonconvexities in the Theory of Externalities. "Journal of Economic Theory", vol. 4.2, pp. 180-199.

[71]. Tavoni, A., A. Dannenberg, G. Kallis and A. Löschel (2011), Inequality, Communication, and The Avoidance of Disastrous Climate Change in a Public Goods Game. Proceedings of the National Academy of Sciences, vol. 108 (29), pp. 11825-11829.

[72]. Tulkens, H. and V. Steenberghe (2009), "Mitigation, Adaptation, Suffering": In Search of Right Mix in the Face of Climate Change. FEEM Working Paper Series 79.2009, Milan, Italy.

[73]. Ulph, A. (1998), Learning about Global Warming? In: Hanley, N. and H. Folmer (eds.), Game Theory and the Environment. Edward Elgar, Cheltenham, UK et al., ch. 13, pp. 255-286.

[74]. Ulph, A. (2004), Stable International Environmental Agreements with a Stock Pollutant, Uncertainty and Learning. "Journal of Risk and Uncertainty", vol. 29(1), pp. 53-73.

[75]. Vives, X. 2005, Complementarities and Games: New Developments. "Journal of Economic Literature", vol. 43.2, pp. 437-479.

[76]. Weikard, H-P. (2009), Cartel Stability Under an Optimal Sharing Rule. "The Manchester School", vol. 77.5, pp. 575-593.

[77]. Yi, S.-S. (1997), Stable Coalition Structures with Externalities. "Games and Economic Behavior", vol. 20(2), pp. 201-237.

[78]. Zehaie, F. (2009), The Timing and Strategic Role of Self-Protection. "Environmental and Resource Economics", vol. 44(3), pp. 337-350.

Figure 1: Downward-sloping Replacement Functions

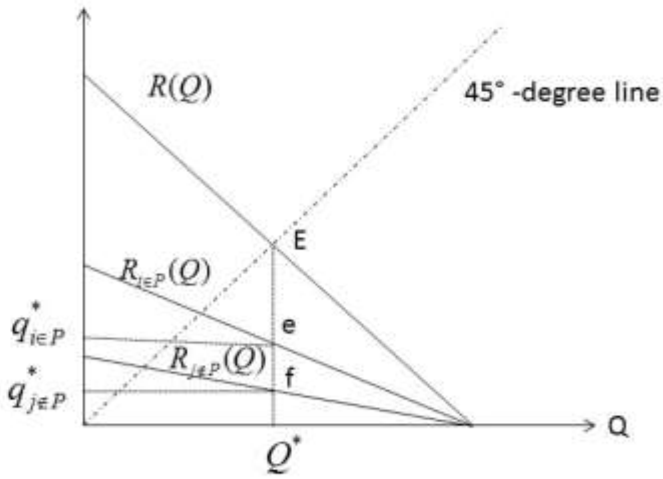

Figure 2: Upward-sloping Replacement Functions

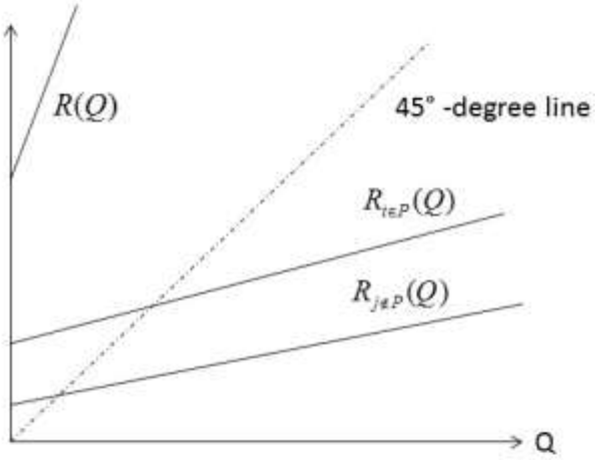

Table 1: Example 1, Simulation Run 1

		$p^{*M+A}(p^{*M})$	$p^{*M+A}(p^{*M})$	$\overline{p}^{*M+A}(\overline{p}^{*M})$
		3 (3)	10 (3)	3.01 (3)
Set 2		2616	4	2620
$\overline{A}$	M+A	28.23	36.15	28.24
	M	0	0	0
$\overline{Q}^{*}(p^{*})$	M+A	0.37	5.65	0.38
	M	1.25	1.42	1.25
$\overline{x}^{*}(p^{*})$	M+A	0.72	0.36	0.72
$\overline{\Pi}^{*SO}$	M+A	14290.3923	14847.1821	14291.24
	M	13539.5394	14742.3964	13540.84
	$\frac{M+A}{A}$	1.0655	1.0071	1.0654
$\overline{\Pi}^{*CO}$	M+A	11731.25	14847.18	11736.01
	M	3872.31	4216.32	3872.82
	$\frac{M+A}{A}$	3.0997	3.5214	3.1003
$\overline{\Pi}^{*NE}$	M+A	11586.4640	14646.2079	11591.13
	M	2572.5125	2801.0502	2572.86
	$\frac{M+A}{A}$	4.6122	5.2288	4.6131
$\overline{I}^{SO}$	M+A	1.25	1.01	1.25
	M	5.26	5.26	5.26
$\overline{I}^{CO}$	M+A	1.0135	1.0138	1.01
	M	1.5	1.5	1.5

N=10, and *a=3000*, $\gamma = \lambda = 0.1$, parameter *b* moves from 300 to 500 in steps of 10, and parameter *c* and *d* move from 3000 to 5000 in steps of 100. Set 1= 9261, Set 2= 2620.

Table 2: Example 2, Simulation Run 2

		$p^{*M+A}(p^{*M}) = \overline{p}^{*M+A}(\overline{p}^{*M})$
		3 (2)
Set 2		18676
$\overline{A}$	M+A	2.277
	M	-0.5651
$\overline{Q}^{*}(p^{*})$	M+A	0.03
	M	0.04
$\overline{x}^{*}(p^{*})$	M+A	0.43
$\overline{\Pi}^{*SO}$	M+A	4.0820
	M	3.8082
	$\frac{M+A}{A}$	1.0805
$\overline{\Pi}^{*CO}$	M+A	2.7102
	M	0.9056
	$\frac{M+A}{A}$	3.0658
$\overline{\Pi}^{*NE}$	M+A	2.5771
	M	0.7698
	$\frac{M+A}{A}$	3.4364
$\overline{I}^{SO}$	M+A	1.5820
	M	4.9577
$\overline{I}^{CO}$	M+A	1.0515
	M	1.1765

N=10, and *a=2.5*, *e=1*, parameter *b* moves from 0.1 to 1 in steps of 0.1, and parameter *c* moves from 500 to 1000 in steps of 10, parameter *d* move from 2 to 2.3 in steps of 0.1, and parameter *f* moves from 2 to 3 in steps of 0.1. Set 1= 22440, Set 2= 18676.

Table 3: Example 2, Simulation Run 3

		$p^{*M+A}(p^{*M})$	$p^{*M+A}(p^{*M})$	$\overline{p}^{*M+A}(\overline{p}^{*M})$
		3 (2)	10 (2)	3.1 (2)
Set 2		3961	6	3967
$\overline{A}$	M+A	4.305	5.03	4.306
	M	-0.5569	-0.35	-0.5566
$\overline{Q}^{*}(p^{*})$	M+A	0.01	0.25	0.01
	M	0.04	0.06	0.04
$\overline{x}^{*}(p^{*})$	M+A	1.03	0.5	1.03
$\overline{\Pi}^{*SO}$	M+A	5.3591	5.6250	5.3595
	M	3.9775	5.5804	3.98
	$\frac{M+A}{A}$	1.3894	1.008	1.388
$\overline{\Pi}^{*CO}$	M+A	5.2316	5.62	5.2322
	M	0.9480	1.3188	0.9485
	$\frac{M+A}{A}$	5.7268	4.2682	5.7246
$\overline{\Pi}^{*NE}$	M+A	5.2240	5.5562	5.2245
	M	0.8055	1.1208	0.806
	$\frac{M+A}{A}$	6.7292	4.9612	6.7265
$\overline{I}^{SO}$	M+A	1.0264	1.0124	1.0264
	M	4.9499	4.9827	4.9499
$\overline{I}^{CO}$	M+A	1.0014	1.0124	1.0014
	M	1.1764	1.1767	1.1764

N=10, and *a=2.5*, *e=1*, parameter *b* and *d* moves from 0.1 to 1 in steps of 0.1, and parameter *c* moves from 500 to 1000 in steps of 10, and parameter *f* moves from 2 to 3 in steps of 0.1. Set 1= 56100, Set 2= 3967.

Table 4: Example 2, Simulation Run 4

		$p^{*M+A}(p^{*M})$	$p^{*M+A}(p^{*M})$	$\overline{p}^{*M+A}(\overline{p}^{*M})$
		1 (2)	2 (2)	1.07 (2)
Set 2		1596	105	1701
$\overline{A}$	M+A	-511.66	-106.66	-486.66
	M	-525	-120	-500
$\overline{Q}^{*}(p^{*})$	M+A	4.45	9.36	4.75
	M	5.65	10.83	5.97
$\overline{x}^{*}(p^{*})$	M+A	3.04	2.71	3.02
$\overline{\Pi}^{*SO}$	M+A	298094	591165	316184
	M	180424	550479	203266
	$\frac{M+A}{A}$	1.9511	1.0920	1.8981
$\overline{\Pi}^{*CO}$	M+A	273464	426031	2822881
	M	154390	351579	166562
	$\frac{M+A}{A}$	2.0426	1.2463	1.9934
$\overline{\Pi}^{*NE}$	M+A	273464	401993	281397
	M	148462	320745	159095
	$\frac{M+A}{A}$	2.1012	1.2923	2.0513
$\overline{I}^{SO}$	M+A	1.0762	1.4540	1.0995
	M	1.169	1.7124	1.2025
$\overline{I}^{CO}$	M+A	1	1.0578	1.0036
	M	1.0328	1.0958	1.0367

N=10, and *c=d=3000*, *e=10000*, *f=200*, parameter *a* moves from 3000 to 5000 in steps 100, and parameter *b* moves from 100 to 900 in steps of 10. Set 1= 1701, Set 2= 1701.

ECONADAPT
The Economics of Adaptation

Funded by the European Union

Chapter Four: Evaluating adaptation options through the elicitation of people's preferences

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Deliverable number	
Work Package Number	
Submission date	
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Evaluating adaptation options through the elicitation of people's preferences
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Work Package Number	WP
Deliverable number	D
Filename:	.doc
Document history:	Draft/ Final and version number
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	
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The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

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Key messages

- Willingness to pay for additional flood and drought adaptation measures as increased monthly bill for water consumption paid by a household ranges from €15 to €19 in the Czech Republic, from €35 to €45 in Italy, and from €33 to €44 in the UK (using market exchange rate).
- In all three countries, **citizens prefer reducing the severity of climate change impacts** as opposed to reducing the number of affected people in the population.
- **British citizens** prefer adaptation programs that **reduce the impacts of floods;** whereas **Czech citizens** consider **reducing the impacts of droughts** a more important objective.
- **Rainwater harvesting** is the most popular measure in all three countries. In the United Kingdom, **large reservoirs and dams** come second in preference; large dams being the least popular measure among Czech citizens.
- Citizens in all three countries express relatively high preference for two nature-based adaptation measures: **creating wetlands** and **changing the use of agriculture land.**

Context

Climate change is expected to impact the water system in many countries, leading to more extreme weather patterns, causing for example higher likelihoods of flooding, drought and heat waves and also increasing the severity of such occurrences.

The research examined preferences of citizens of three European countries, the Czech Republic, Italy and the United Kingdom, for adaptation plans and measures to limit damages from floods and droughts. For this purpose, the researchers conducted a questionnaire survey in the three European countries. They used two discrete choice experiments to elicit individual preferences for adaptation options (the first one focused on trade-off between severity and size of droughts and flood risks, the second one aimed at specific adaptation measures) and applied standard econometric models to estimate marginal willingness-to-pay for the attributes of adaptive policies.

Policy and methodological developments

The questionnaire survey took place in the Czech Republic, the United Kingdom and Italy between 23rd June and 14th August 2016. The three countries exemplify different political and socio-economic settings for the purpose of comparison. The survey included residents of these countries aged from 18 to 69 years. Data were collected through online access panels using web-based questionnaires. The final sample includes in total 7,042 valid observations.

In the discrete choice experiments, respondents were asked to choose their preferred adaptation policy described by several characteristics, such as type of structural technical measures. One of the characteristics was increased monthly bill for water consumption paid by a household, which allowed the analysts to estimate willingness to pay for climate adaptation policies. The costs were shown on the choice cards in national currencies of the three countries, but represent the same amounts in purchase power standards (PPS). The estimates of marginal willingness-to-pay for the characteristics of adaptive policies expressed in nominal euro are summarised in Table 1 and Table 2.

Table 1: Implicit WTP values for the types of adaptation measures, in nominal euro per month and household (second discrete choice experiment on specific adaptation measures); estimates in the brackets are statistically not different from zero.

	Droughts			**Floods**	
	Czech	**Italy**	**UK**	**Italy**	**UK**
Structural technical measures					
Large reservoirs and dams	9.4 €	15.7 €	24.8 €	27.4 €	18.2 €
Small water reservoirs and ponds	14.8 €	17.3 €	17.4 €		
Rainwater harvesting	16.4 €	28.5 €	23.9 €		
Floodwalls, dikes				32.1 €	16.0 €
Flood-resistant materials				33.2 €	14.8 €
Maintenance of river beds				56.4 €	25.5 €
Restoration of buildings (ex post)				26.3 €	11.8 €
Structural nature-close measures					
Creating wetlands (Flood: … or woodlands)	15.5 €	14.3 €	20.2 €	31.1 €	32.4 €
Drought: Changes in the use of agricultural land Flood: Restoration of natural areas (ex post)	15.4 €	17.5 €	18.6 €	21.1 €	18.6 €
Green roofs on public buildings				11.2 €	16.9 €
Non-structural soft measures					
Drought: Information on efficient water use Flood: Information provision	5.4 €	21.0 €	11.5 €	15.7 €	*(4.0 €)*
Drought: Drought risk management plans Flood: Control on construction in vulnerable areas	6.3 €	20.2 €	9.2 €	40.0 €	31.7 €
Improved land use planning	6.0 €	18.6 €	10.6 €		
Tax relief on … (Drought: water efficient technologies) (Flood: flood protection measures)	6.0 €	23.0 €	7.6 €	24.3 €	15.5 €
Tax relief for floods victims (ex post)				22.7 €	17.0 €

Higher charges (Drought: for large water extraction) (Flood: council tax in flood-prone areas)	*(0.3 €)*	6.6 €	5.7 €	*(4.9 €)*	*(0.8 €)*
Water consumption restrictions *(ex post)*	3.2 €	13.1 €	4.8 €		
Provision of flood insurance				12.7 €	22.1 €
Proportion of people at risk	*(0.3 €)*	1.2 €	1.2 €	*(- 0.0 €)*	2.1 €

Table 2: Implicit WTP values for reducing severity and size of the impact associated with droughts or floods, in nominal euro per month and household (first discrete choice experiment)

	Czech Republic	Italy	United Kingdom
floods: small impacts	6.2 €	15.8 €	27.2 €
floods: medium impacts	7.5 €	16.4 €	22.4 €
droughts: small impacts	11.4 €	15.1 €	22.1 €
droughts: medium impacts	9.4 €	14.2 €	16.0 €
floods: size reduced by each percentage point	(0.3 €)	1.8 €	1.9 €
droughts: size reduced by each percentage point	1.6 €	1.9 €	1.5 €

Note: Severity of the impacts is compared to large impacts (reference category), while the size of the impacts is compared to expected percentage of people at risk without additional adaptation measures. The estimate in the brackets is not virtually different from zero.

While more than half of Italians and Czechs expect that their households will be exposed more often to impacts of heat waves and droughts over the next 10 years, only about 20 % of British are of the same opinion. The majority of British (67 %) think that they will be affected by heat waves and droughts with the same frequency.

Only small part of survey participants from all three countries expects frequency of floods to increase (18 % of Italians, 10 % of British and 8% of Czechs). Moreover, about a third of Italian and British respondents and 44 % of Czechs do not perceive to be at risk of flooding.

Most Italians and Czechs perceive droughts as a great risk for their households and relate droughts to climate change. More frequent droughts is the most often expected climate change impact on the respondents' region and on respondents themselves from all consequences that were listed. Even half of Italian respondents think that they will be more vulnerable to drought. However, this is not the case for the British who agree with these statements much less (only 37 % agree that droughts will be consequences of climate change for their region and 24 % for themselves).

A large share of people (47 % in the Czech Republic, 43 % in the UK, and even slightly more than half of Italians) perceive climate change as a serious problem for animals and plants and their habitats. Respondents see negative effects more likely to occur than positive ones. The least expected effect of climate changes in all countries is an improved economic situation both at regional and personal level. People are also rather sceptical about fewer winter related diseases and deaths. Compared to other countries, a larger share of Italians connects climate change with negative impacts and disagrees that climate change could have some positive impacts both at regional and personal level.

While Italians tend to perceive regulation of construction in vulnerable areas and maintenance of river beds or streams to be the most effective measures to limit flood damage, the British rate them less effective. Moreover, river beds or streams are not sufficiently maintained in Italy according to respondents. Also several other measures are perceived by Italians as less implemented than by the British, namely construction of buildings and infrastructure from flood-resistant materials, green roofs on public buildings, and restoration of natural areas after flooding, creating woodland or wetlands.

Most respondents view rainwater harvesting as effective. However, in the Czech Republic almost the same share of respondents (about 60 %) evaluates two nature-based adaptation measures (specifically creating wetlands and changing the use of agriculture land) as equally effective as rainwater harvesting. Half of Italian respondents and 43 % of British respondents find changing the use of agriculture land especially effective. British also rate building large reservoirs and dams as second most effective, while building large dams is the least effective measure among all structural measures for Czechs.

A much larger share of respondents from Italy thinks that a tax relief on water efficient technologies, information provision, and risk management plans are effective adaptation options than shares in the Czech Republic and in the UK. Higher charges for large water extraction are the least effective measure among all presented measures.

Only a small share of respondents perceives that the structural measures to limit drought damage are introduced sufficiently (ranging from 14 % to 25 %). Czechs are more critical than respondents from the other countries in evaluating level of implementation of several measures, specifically rainwater harvesting, creating wetlands and changes in the use of agriculture land. A third of Czechs perceives these measures as insufficiently implemented. About third of British and Italians are satisfied with the degree of implementation of water consumption restrictions and the degree of information provision.

Main implications and recommendations

The results show differences in willingness-to-pay between floods and droughts, specific structural measures (natural and technical) and non-structural soft measures, and among the three countries.

In all three countries, citizens expressed considerably high value of willingness to pay for additional adaptation measures for flood and drought prevention.

Citizens prefer measures which reduce the severity of climate change impacts (from large impacts to either medium, or to small impacts) over measures which reduce the number of affected people (expressed in percentage of people at risk).

Also, citizens prefer rainwater harvesting as a measure compared to other nature-based and technical measures.

Policy makers from the UK, Poland and the Czech Republic can increase public support for their adaptation plans and measures by following the preferences described in this research. Policy makers from other countries may choose to use this information as a starting point for a separate inquiry at the local, regional or national level.

Policy makers can feel free to contact the researchers for assistance in utilizing the results.