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Outlines of a New Research Programme

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Summary. In view of the failure of international negotiations on climate protection and the improbability of a trend reversal in the climate changes that have already occurred, the option of climate change adaptation is becoming more and more important in climate change policy. A large number of countries have already initiated a process of adaptation by drafting strategies or catalogues of measures. Hence there is an urgent need to support this process at the scientific level. The discipline of economics has a key role to play in this context, especially with regard to the design, evaluation and selection of adaptation measures and instruments. The still relatively young field of research into the economics of adaptation is growing at a considerable pace and already exhibits a wide range of methodological approaches and research questions. Against this background, the present report aims to undertake a systematic structuring and synthesis of the individual research studies in order to provide political actors with an overview of the scientific recommendations and findings they must consider when making decisions. Another aim of the report is to identify open research questions and, based on this, to outline key pointers for the future direction of the research into the economics of climate adaptation.

Key words: Climate change, climate policy, adaptation, barriers, governance, instruments, literature overview, economic research, goal setting

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Contents

1 The Economics of Climate Adaptation – A New Field of Research

1. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a), warming of the Earth's climate is now evident. This follows from observations of increases in global average sea and air temperatures, widespread melting of snow and ice, as well as a rise in the global mean sea level. Furthermore, on all continents and in most oceans, numerous natural systems have already been affected by regional changes in climate. It is, moreover, highly likely that the global warming now being observed can be traced back to increases in anthropogenic greenhouse gas emissions.

2. Leaving climate engineering[1] aside, there are two basic climate policy options with which to respond to the problems and challenges of human-induced climate change such as the increasing intensity and frequency of extreme weather events or the threat posed by rising sea levels to coastal settlements: First, climate change can be curbed or halted by reducing greenhouse gas emissions (**mitigation**). Secondly, measures can be taken to adapt society and ecological systems to the changed climatic conditions (**adaptation**).

3. In view of the failure of international negotiations on climate protection and the improbability of a trend reversal in climate changes which have already occurred, **the climate adaptation option is becoming increasingly important in climate change policy** (see e.g. FANKHAUSER, 2009, IPCC, 2001, PIELKE et al., 2007 and HANSJÜRGENS and ANTES, 2008). Moreover, climate adaptation is already on the agenda in (environmental) political practice. Numerous countries have initiated a process of adaptation by drafting strategies or catalogues of measures (for the European Union see PEER, 2009). Hence there is an urgent need both to support this process at the scientific level and to communicate the respective findings and derive recommendations for policy advice.

4. The **discipline of economics** has a **key role** to play in this context, considering that the aim is not only to provide the appropriate **incentives and framework conditions** for successful, independent adaptation of the actors concerned but also, where this is not possible, to **ensure that the interventions of government institutions in adaptation policy are designed and implemented efficiently**. This still relatively young field of research into the economics of adaptation is growing at a considerable pace and already features a huge range of methodological approaches and research questions. Against this backdrop, **a systematic structuring and synthesis of the individual research studies** is essential in order to provide political actors with an overview of the scientific recommendations and findings they must consider when making decisions. Secondly, scientists themselves need to gain an insight into the state of research in the field in order to identify open research questions so that the research process can be set on the right course.

[1] More recently, "climate engineering" is increasingly being discussed as a third option. This field envisages (mostly technical) interventions in the Earth's climate system to reduce the greenhouse effect caused by *existing* GHG emissions. Given the massive uncertainties surrounding the effectiveness, costs, and environmental effects of such interventions, the scientific community sees geo-engineering at best as an emergency option for the future, one that is not, however, to be considered at present (see SHEPHERD, 2009; and, more recently, GAWEL, 2011 on the current research landscape).

5. The **present report** attempts to address these concerns by providing a structured overview of the literature. The **approach** taken is as follows: Basically all works dealing with the economics and politics of climate adaptation on the basis of theoretical or empirical methods will be covered. These also include works with a background in the social or political sciences which display links to economics. First of all, Chapter 2 defines the boundaries of the "Economics of Climate Adaptation" research field, dividing it into different sub-fields, each of which deals with a specific set of themes. The scientific papers in the individual sub-fields are summarised and presented in Chapters 3-6 and classified according to their place in the complex as a whole. Chapter 7 is dedicated to works which are specifically designed to support political decision makers in the adaptation process and which provide pertinent recommendations, guidelines and orientation aids. Chapter 8 provides an overview of the different methodological approaches applied in the individual sub-fields. Chapter 9 compares the key issues of the research into the economics of adaptation with those of adaptation policy, which allows certain conclusions to be drawn in relation to the direction of the research and communication between scientists and politicians. Chapter 10 sketches the German research landscape in terms of research priorities. Finally, Chapter 11 summarises the findings of the report and identifies open research questions and challenges for future research into the economics of adaptation.

2 Adaptation and Economic Research: Boundaries and Challenges

6. This section first conducts an inventory and defines the boundaries of the economics of adaptation research field. For this purpose, Section 2.1 defines the **terminology** necessary for a basic understanding of the remainder of the report (No. 7) and points out the different **dimensions of climate adaptation** (Nos. 8-15). In addition, the fundamental **characteristics** of **adaptation** are compared with those of the alternative climate policy strategy (mitigation) (Nos. 16-18). Section 2.2 structures the economics of adaptation field and provides an **overview of the different thematic areas** referred to in the research.

2.1 Concept and dimensions of climate adaptation

7. The **definition** put forward by the Intergovernmental Panel on Climate Change (IPCC, 2001) has been broadly accepted in the literature: in many works it is adopted in its original form (e.g. FÜSSEL, 2007 or ADGER et al., 2005) or with minor modifications (e.g. GTZ, 2007 or TOL, 2005): "*Adaptation is adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. This term refers to changes in processes, practices, or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate. It involves adjustments to reduce the vulnerability of communities, regions, or activities to climatic change and variability*."

8. From this definition emerge the three **dimensions** of adaptation described by SMIT et al. (1999) on the basis of the questions 'Adaptation to what?' (climate-related stimuli), 'Who/what performs the adaptation?' (adaptation system) and 'How does adaptation occur?' (adaptation measures) – see Figure 1.

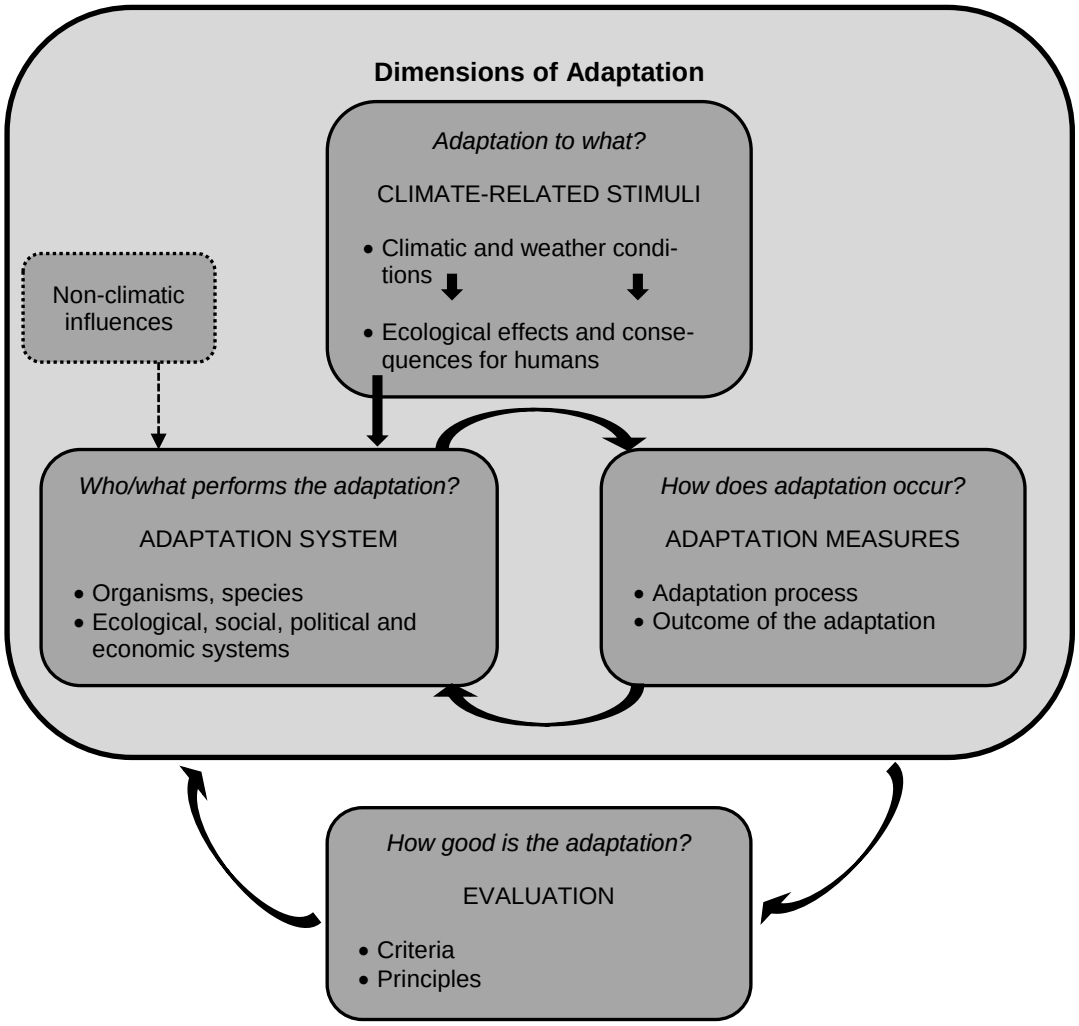

Figure 1: Dimensions of Adaptation (SMIT et al.,1999)

9. The grounds for adaptation are provided by **climate-related stimuli**, i.e. altered weather or climate conditions (e.g. precipitation or temperature) and the resulting ecological or economic impacts (e.g. droughts, crop failures, income losses) that are clearly linked to the sensitivity of the (adaptation) system under observation (No. 10). In terms of the **temporal dimension** essentially three types of stimuli are to be differentiated: long-term changes in average values and norms, within-year or within-decade variability as well as isolated extreme weather events or catastrophic weather conditions such as flooding, hail or storms. These types are not independent from each other, rather they mutually determine and influence each other: Extreme events are part of the variability of certain weather and climate parameters. Variability is in turn decisively influenced by the long-term development of the parameters. Furthermore, the stimuli exhibit different **spatial characteristics**, i.e. they occur in a locally limited area or are spread over a wide area. Finally, it should be noted that the adaptation system, in addition to the climate-related stimuli, is also subject to various **non-climatic influences**, such as population growth or decline, which can amplify or diminish the effects of the original climatic stimuli and should thus be considered in the adaptation.

10. Adaptation occurs in the **adaptation system**. First the latter is to be defined according to the level at which the adaptation takes place (SMIT et al., 1999). For example, adaptation at the level of an agricultural holding comprises crop diversification, whereas at a global level it can manifest as a shift in the international food trade structure. Furthermore, the definition refers to the nature of the adaptation system, which may be ecological, political, social or economic in character or may encompass a combination of these components. Finally, the system has to be differentiated according to who performs the adaptation (e.g. coastal protection managers) and what modifies itself or is modified (e.g. coastal settlements).

11. Once the system has been defined, it can then be **characterised** on the basis of various criteria. SMIT et al. (2000) summarise the criteria established in the literature, which are partially overlapping – cf. Table 1. These criteria essentially characterise the system according to how great the **adaptation requirement** is, with what **probability** the adaptation will take place, and to what extent it has the **capacity to adapt**. The determinants of adaptation probability, e.g. resistance or flexibility, embody to some extent the necessary preconditions for sufficient adaptability/adaptive capacity of the system and therefore only characterise it indirectly. A comprehensive description of the system based entirely on the criteria of adaptation requirement and adaptive capacity is therefore possible (SMIT et al., 2000). The key concepts put forward in the literature in this context are **sensitivity, vulnerability** and **adaptability** or **adaptive capacity**. The following example aims to illustrate how these are connected: A coastal settlement area (adaptation system) is sensitive to storms (a reoccurring climate-related stimulus, part of variability) because they cause significant changes in the local environment, which are subsequently reflected in living conditions and infrastructure. In this context the vulnerability of the settlement area refers to its susceptibility to adverse effects emerging from the above-mentioned changes, such as contamination of drinking water or damage to property. In this example the system's ability or capacity to adapt is determined, among other things, by knowledge and awareness with respect to storm hazards, emergency planning, early warning systems, and the planning and implementation of storm-resistant construction projects.[2]

[2] The Intergovernmental Panel on Climate Change (IPCC, 2001b) and GOKLANY (2007) refer to access to technology, resource availability, information and skills/capabilities, infrastructure and institutions, as well as human and real capital as general determinants of adaptive capacity. KELLY and ADGER (1999) regard adaptive capacity and vulnerability as mirror-image concepts as can be seen from their definition of the term vulnerability: "…*we define vulnerability in terms of the capacity of individuals and social groups to respond to, that is, to cope with, recover from and adapt to, any external stress placed on their livelihoods and well-being*".

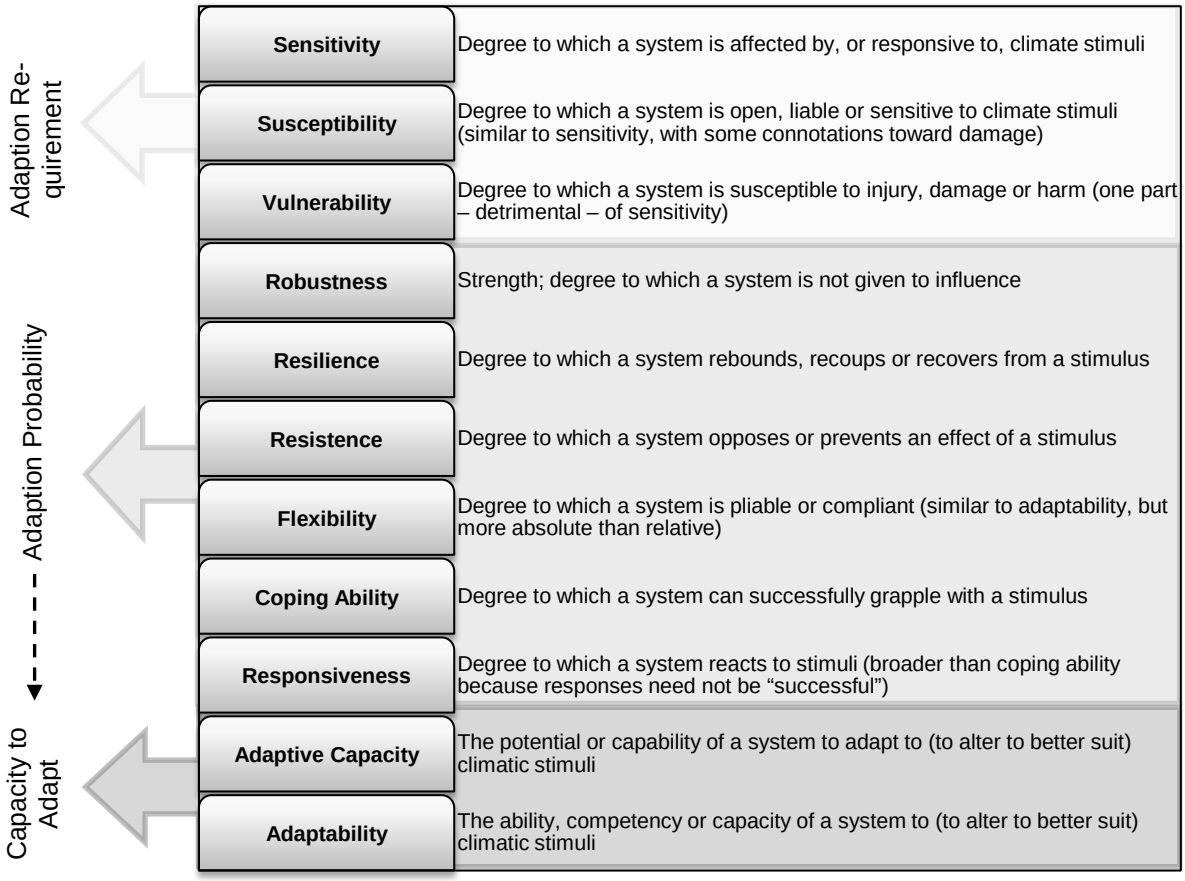

Table 1: Characterisation of the adaptation system (following SMIT et al., 2000)

12. An **alternative characterisation of the adaptation system** is presented by REILLY and SCHIMMELPFENNIG (2000), who focus on aspects of the short- and long-term autonomous and non-autonomous flexibility of the system as well as the availability of the required knowledge for implementing the adaptation. ADGER et al. (2005) delve further into the question of which **actors** make the adaptation decisions. They differentiate in this context between individuals, businesses, civil society, public authorities, government at local, regional and national level as well as international organisations.

13. The last adaptation dimension focuses on the question of how, i.e. with what measures, the adaptation system confronts climate-related stimuli. Table 2 shows the **characterisation of adaptation measures** according to SMIT et al. (1999), which has become established in the literature as the current standard (FÜSSEL, 2007, FÜSSEL and KLEIN, 2004 and IPCC, 2001). The measures are thereby described according to the following criteria and attributes: The **purposefulness** of the measure refers, among other things, to whether it occurs **autonomously**[3] or **spontaneously** or whether it was purposefully planned and whether it is part of

[3] AAHEIM and AASEN (2008) subdivide autonomous adaptation into direct (changes in technologies/preferences as a reaction to climate change) and indirect (market reaction to changes in technologies/preferences) components.

a natural or political process. Autonomous adaptation is frequently equated with private adaptation, which is the counterpart of policy-driven or public adaptation. With regard to **timing**, a distinction must be made as to whether the measure is taken as a reaction to a climate-related stimulus or whether it is taken proactively – cf. SMITH (1997).[4] FANKHAUSER et al. (1999) point out that the **relationship** between anticipatory/planned and reactive/autonomous measures is both **complementary** and **substitutive**, i.e. the measures can benefit or compromise each other. For instance, changes in supply and demand are more rapidly reflected in the price of grain after the elimination of grain subsidies, promoting a quicker response to climatic changes among farmers. In this case, therefore, the anticipatory/planned measure increases the marginal utility of the reactive/autonomous measure (complementary relationship). By way of contrast, a substitutive relationship exists when for instance anticipatory/planned coastal protection measures, such as the construction of dyke systems, reduce the affected population's need for reactive/autonomous adaptation measures. The **temporal scope** describes, among other things, whether the measure is created for the short or long term, and whether it is implemented tactically to cope with an immediately imminent situation or strategically to adapt to the longer term impacts of climate change. In terms of the **spatial dimension**, the measure can be designed for a local area or for a wider area. The prevention of damage or its elimination, for example, should be considered as possible **functions** and **effects**. Finally, the different **forms** of the measures, e.g. legal, financial or technological, have to be distinguished. The manifestation of all the attributes mentioned depends on the other two dimensions of adaptation: For example, the adaptation of natural systems which are free from human interference inevitably occurs autonomously and reactively, whereas adaptation measures induced by public authorities are usually planned and possibly anticipatory (SMIT et al., 1999). Moreover, climate-related stimuli that cause long-term effects, such as the increase in average temperature, call for anticipatory and/or strategic measures, whereas extreme events which are difficult to predict, such as flooding, require reactive and/or tactical measures.

[4] FÜSSEL and KLEIN (2004) refined the category of proactive adaptation with regard to different *stages of prevention*: primordial (addresses the root cause of the potential damaging event, therefore a smooth transition to mitigation) – primary (prevention of the event by reducing the susceptibility of the system to the hazards inherent in climate change) – secondary (exposure of climate-induced changes relevant to the system and introduction of measures targeted at these) tertiary (reaction to changes and/or damages that have already occurred in order to avoid more far-reaching consequences).

General Differentiating Concept or Attribute	Examples of Terms Used	
Purposefulness	autonomous spontaneous automatic natural passive	planned purposeful intentional policy active strategic
Timing	anticipatory proactive ex ante	responsive reactive ex post
Temporal Scope	short term tactical instantaneous	long term strategic cumulative
Spatial Scope	localised	widespread
Function/Effects	retreat – accommodate – protect prevent – tolerate – spread risk – change – restore	
Form	structural – legal – institutional – regulatory – financial – technological	
Performance	optimality – efficiency – implementability – equity	

Table 2: Categorisation of Adaptation Measures (SMIT et al., 1999, p. 208)

14. In contrast to these purely descriptive attributes of the adaptation measures, the attributes related to their **performance** are equally descriptive and evaluative. Here the evaluation of the measures is tied to criteria such as effectiveness, cost-efficiency, efficiency or optimality, implementability or equity (see Section 3.3 for further details). A holistic evaluation of the performance of a measure must take place in the context of the triggering stimuli as well the affected adaptation system (cf. SMIT et al., 1999 and Figure 1). The findings gained from the evaluation should then be taken into account in the future selection and implementation of the measures.

15. The following works **deviate somewhat from the standard set by SMIT et al. (1999)** (No. 11): CIMATO and MULLAN (2010) differentiate the adaptation measures according to how they confront threatened, climate change-induced losses (prevention, toleration or division of losses). ADGER et al. (2005) and the IPCC (2001b) distinguish between building adaptive capacity and the implementation of adaptation measures. A classification according to the relative weight of climate- and non-climate-related influencing factors of the adaptation measures is proposed by FÜSSEL and KLEIN (2004). Following up on this, a number of authors point out that adaptation measures are not always readily differentiable because they frequently overlap with other arenas of political activity such as education and development policy or civil protection (FÜSSEL, 2007, MERCER, 2010, and OECD, 2008).

16. In the discourse on climate policy **adaptation** is regularly motivated as a necessary, complementary strategy to **mitigation** (e.g. BUCHHOLZ and RÜBBELKE, 2011). Therefore, finally, a comparison of the **fundamental characteristics** of both of these strategies is rec-

ommended in order to ensure a clear differentiation of the concept of adaption. Such a comparison is carried out by FÜSSEL (2007) and by FÜSSEL and KLEIN (2006) – see Table 3. Traditionally, mitigation receives greater attention than adaption, both from the scientific and from the political angle. This is largely due to the following characteristics of the two options: The mitigation of greenhouse gas emissions can avert negative **effects of climate change on all climate-sensitive systems**, whereas in many systems the scope for adaptation is limited – just think of small (and mostly also poor) island states that are virtually defenceless against rising sea levels. Moreover, the **effectiveness** and/or **benefits** of mitigation (in the long-term perspective) are certain because mitigation combats climate change-related problems directly at the source. In contrast, the effectiveness of (proactive) adaptation frequently depends on predictions about the regional vulnerability situation and the related consequences of climate change, which are **associated with high levels of uncertainty**. Also mitigation naturally complies with the **polluter pays principle**. The situation is different for adaptation: Developing countries generally demonstrate the greatest need for adaptation even though, in the context of their historic emissions, they have contributed far less to climate change than the industrial nations. Finally, obtaining quantitative data on greenhouse gas emissions is relatively unproblematic, making it easier to **monitor the success** of mitigation efforts. It is much more difficult to measure the effectiveness of adaptation measures. Due to its heterogeneity and multifacetedness, no universal measure of success exists for adaptation, in contrast to the mitigation option (quantity of emissions saved) (CIMATO and MULLAN, 2010).

17. However some characteristics of the two climate policy options favour stronger consideration of adaption. In view of the **scope** of their effects, adaptation measures can be implemented at local or regional level. The situation is different for mitigation, the effectiveness of which depends on collective global efforts. So, as a consequence, the **bearer of the costs** of an adaptation measure profits almost fully from it, whereas the benefit from a single mitigation measure is only marginal. In short, adaptation is typically a private,[5] mitigation a public good, which is subject to the free-rider problem. Moreover, compared with mitigation, adaptation measures are often associated with an **added benefit**, in particular in terms of reducing the risks of current climate variability. With regard to the **lead time**, it can be stated that the benefits of (reactive) adaptation measures are often immediately effective, whereas the effect of mitigation will only kick in after a delay of several decades due to the inertia of the climate system.

[5] For exceptions and barriers in the private provision of adaptation measures see Section 4.2.1.

	Mitigation	Adaptation	
benefitted system	all systems	selected systems	Advantage Mitigation
effectiveness/benefits	certain	generally uncertain	
polluter pays principle	typically yes	not necessarily	
monitoring success	relatively easy	more difficult	
scale of the effect	global	local to regional	Advantage Adaptation
payer benefits	only little	almost fully	
added benefit	sometimes	frequently	
lead time	decades	none up to decades	

Table 3: Fundamental characteristics of mitigation and adaptation (following FÜSSEL and KLEIN, 2006)

18. TOL (2005) groups the different characteristics of adaptation and mitigation into the following three categories. First there is a **discrepancy in the basic scope of action** of the two options. While mitigation efforts are part of the area of competence of national governments against the backdrop of international climate protection negotiations, adaptation measures are primarily implemented by local managers of natural resources, households and firms within the context of the regional socio-economic environment. Even though emissions mitigation is ultimately carried out by individuals, it is the government that provides the appropriate incentives. Furthermore, TOL (2005) points out that the **tools to support decision making** relating to the planning and implementation of mitigation and adaptation measures such as benefit-cost analyses (see No. 62) are directed at **different addressees**. In the case of mitigation, the tools are of interest primarily to the Ministry for Energy and Finance, and secondly to the Ministry for Transport, Land and Forestry as well as the Ministry of the Environment. In the case of adaptation, on the other hand, the relevant clientele includes local water or coastal protection management institutions, farmers, health officials, tourist facilities, architects and energy producers. Here decision makers at national level are only involved on the margins. Finally, there is also a discrepancy in terms of the **temporal scope of the decision-making support**. The focus in the case of the mitigation option is on short-term measures that are aimed at preventing long-term adverse effects; in the case of the adaptation option, it is mostly short-term measures targeted at short- to long-term developments. In view of these discrepancies TOL (2005) and, following on from this, FANKHAUSER (2009) come to the conclusion that the two options should in general be examined independently of each other because the foundations for a joint analysis framework are not given. TOL (2005), however, sees so-called **facilitative adaptation** as an **exception**. Essentially this belongs to the category of planned, anticipatory adaptation and includes measures which contribute to building adaptive capacity thus creating, according to the principle of subsidiarity, the conditions for successful autonomous adaptation of the affected actors. These include, for example, basic research, the development of infrastructure, the creation of institutions or the communication of information relevant to adaptation. According to TOL (2005), such measures move in similar scales and dimensions to mitigation and could therefore be examined jointly with mitigation.

2.2 Structure and thematic areas of the research field

19. As mentioned at the outset, the field of economic adaptation research is growing at a considerable pace and has already generated a remarkably wide range of thematic areas. In order to fulfil the aims of this report – to create an overview (of the literature) for scientists and decision makers and to identify open research questions – **a clear structuring of the research field** is essential. In the literature, **different starting points** are proposed. AAHEIM and AASEN (2008) outline the basic logic behind the research on the economics of adaptation: Essentially the aim is to determine how climate change influences economic constraints and, building on this, to use economic models to predict and evaluate adaptation behaviour and the associated consequences. SMIT et al. (1999) suggest that the research be oriented along the dimensions of adaptation (climate-related stimuli, adaptation system and adaptation measures, see No. 8) set out by them. The two basic tasks of adaptation research according to SMIT et al. (1999) and the IPCC (2001b) should also be considered as a further structuring option: On the one hand, **positive analysis**, i.e. the prediction of the extent to which adaptations are made, with the ultimate goal of being better able to estimate the effects of climate change; and on the other hand, **normative analysis**, i.e. the derivation of recommendations for adaptation policy as well as the evaluation of policy measures. The task of **descriptive analysis**, which simply comprises a description of the three adaptation dimensions mentioned, should also be added in this context. Finally, REILLY and SCHIMMELPFENNIG (2000) consider structuring adaptation research according to what **type of adaptation system** the research is dealing with. They base this on the typology which they conceived with regard to the short- and long-term autonomous and/or non-autonomous flexibility of the system as well as the adaptation-relevant knowledge present in the system (No. 12).

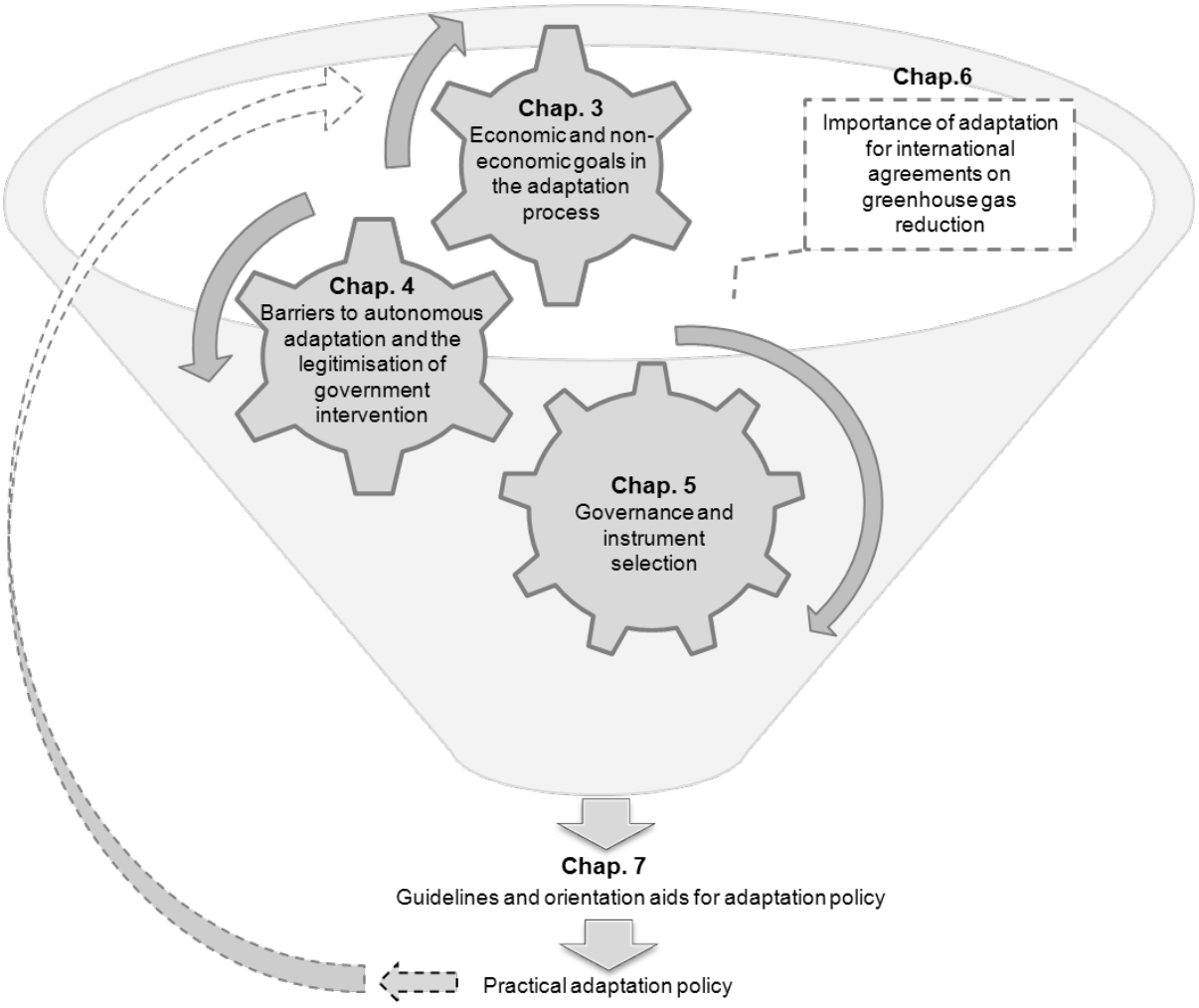

Figure 2: Thematic areas of the Economics of Climate Adaptation research field and structure of the literature overview

20. In terms of structuring, the present report follows the suggestions put forward by SMIT et al. (1999) and the IPCC (2001b), i.e. it is structured according to the adaptation dimensions that are the subject of the research and according to whether the analysis is of a descriptive, positive or normative nature. On the other hand, the report attempts to illustrate the logical sequence of the research questions with respect to content. Figure 2 illustrates the resulting **thematic areas** and also shows the **structure of this literature survey**. The adaptation process begins with a normative question: On which **goals** should the design of individual adaptation measures, their selection and allocation as well as the determination of the adaptation level of a system be based (Chapter 3)? From an economics perspective the concept of optimality or efficiency is at the fore. Non-efficiency-related goals are listed as, among others, (distributive) equity, ecological criteria or security of supply. The second central thematic area stems from the necessity to examine whether the autonomous adaptation of private actors, which is coordinated by the market mechanism, achieves the mentioned goals or whether these are missed due to certain **barriers** (positive analysis). Because, from an economics perspective, **government intervention in the adaptation process** is only **necessary** and **legitimate** in the latter case (Chapter 4). Barriers of this type may manifest them-

selves in classic market failures or in institutional-organisational, regulatory or behavioural obstacles that imply a sub-optimal market result. Then again, it should be taken into account that goals which are unrelated to efficiency, such as equity, are generally not conveyed through the market mechanism and hence can only be brought about by it, if at all, by coincidence. The next logical step is to determine which government **instruments** and **institutions** can be used to overcome barriers to autonomous adaptation and which **governance structures** are necessary to allow this (Chapter 5). Here the analysis is divided into three parts. First a descriptive summary of the possibilities for intervention and structures is presented. The aim of the second step is to identify on the basis of a positive analysis potential barriers that prevent the government intervention having the desired effect. Taking the resulting findings into consideration, normative recommendations can then be derived concerning the design of adaptation policy and the choice of instruments. In addition to the three directly intertwined thematic areas already described (objectives of the adaptation process – legitimisation of government interventions – governance and instrument choice), another area has emerged which to some extent occupies a special position in the research on the economics of climate adaptation - the (positive) analysis of the **role of adaptation in international agreements on reducing greenhouse gas emissions** (Chapter 6). Here it is not the adaptation option that is at the centre of attention but rather the mitigation option. The former is only of indirect interest with respect to its effect on the stability and success of agreements. The findings from all of the areas mentioned up to now are ultimately channelled into studies aimed at providing actors in the area of adaptation policy with **guidelines and decision-support** for implementing government adaptation measures or interventions (Chapter 7). The experiences and insights that emerge from the practical application of adaptation policy provide both new input and new starting points for the science. The process of research into the economics of climate adaptation is therefore dynamic in nature and is absolutely dependent on the aforementioned political feedback for its further development.

3 Climate Adaptation Goals

21. The starting point for the research on the economics of adaptation is the **definition of goals**: to what extent, in what areas and at what point of time should a society perform adaptation to climate change? The **fundamental purposes** of climate adaptation, the reduction of vulnerability of climate-sensitive systems as well as the resistance to and exploitation of climate-change-induced risks and opportunities, respectively, emerge directly from the definition of adaptation (No. 7). The aim of the next step is to operationalize these objectives taking fundamental technical and/or scientific premises into account, that is, to transfer them into concrete (preferably quantifiable) requirements regarding the design of individual adaptation measures, their choice and allocation as well as the determination of the adaptation level of a system. When it comes to the problem of designing the “best possible” adaptation, different standards are available: here a differentiation must be made between the **economic goal** of optimality or efficiency on the one hand (Section 3.1) and **non-efficiency-related goals**, such as security of supply or ecological objectives on the other hand (Section 3.2). Because adaptation is a complex, heterogeneous and problem-specific phenomenon with multifarious effects on the respective social and natural systems (see Chapter 2), in practice adaptation policy is often confronted with multiple objectives which are, as far as possible, to be achieved simultaneously. The realisation of one or more of the objectives mentioned re-

quires the evaluation and selection of adaptation measures and/or sets of measures on the basis of specific criteria and processes, which will be introduced in Section 3.3.

3.1 Optimality

22. In the economic literature on adaptation goals **the demand for optimality or efficiency** dominates, i.e. the respective degree or measure of adaptation chosen should always maximise the net benefit from the societal perspective. The current literature comprises, on the one hand, approaches which **theoretically underpin** the optimality objective (Section 3.1.1) and, on the other hand, efforts to provide an **empirical assessment** of the benefits and costs of adaptation (Section 3.1.2) – a fundamental requirement for the actual implementation of optimal adaptation measures. Noteworthy at this point is the **review** by AGRAWALA et al. (2011), which contains a detailed summary of economic studies and modelling approaches that deal on a theoretical and empirical level with the optimal design, the benefits, and the costs of adaptation. This review differs from the present chapter in two respects. First of all, by categorising the studies into "bottom-up" and "top-down" approaches (No. 46), it is based on a different systemisation of the literature. Secondly, because it focuses exclusively on the optimality or benefit-cost ratio of adaptation, it can give a more comprehensive presentation of the respective works.

23. Unlike mitigation, the adaptation option is multifaceted and heterogeneous, that is, it comprises various measures and is bound to the local/regional context (cf. No. 18). Hence, for a better understanding of the following sections, a brief explanation of the exact meaning of **the term "optimal adaptation"**, which is sometimes used in a relatively abstract sense (e.g. BOSELLO et al., 2010 or MENDELSOHN, 2000), and its dimensions is given here (see also Figure 3). First, on the micro-level the **individual adaptation measure** is the focus of attention. Here the optimality requirement demands that the measure is only taken if its benefit outweighs its cost, in other words, if a positive net benefit results. Likewise, so long as there is scope for manoeuvre in the design of the measure, this should be used in order to bring about the maximum net benefit of the measure. If one increases the level of aggregation of the analysis one arrives at a constellation where to **solve a specific problem**, for instance the threatened flooding of an area, **several alternative measures** are at hand (e.g. the construction of dams or the evacuation of the area). Here it is important to identify the measure with the greatest net benefit and to ultimately implement it. Naturally, there is also the possibility that the sum of a combination of several measures promises a greater net benefit than the individual measures. When implementing several measures, potential interactions have to be taken into account, requiring a corresponding coordination effort (cf. No. 13 and HALLEGATTE, 2009). Given further aggregation one approaches the problem as it appears in, for instance, regional adaptation policy. Here **simultaneous adaptations** are necessary **in several fields of action**, such as flood protection, agriculture and health, for each of which a set of measures is available. In this context, optimality demands the choice of combinations of measures which, when summed up, promise to deliver the greatest net benefit. Again, in doing so, potential interactions between the measures – also in different fields of action – have to be taken into consideration. By means of repeated increases in the level of aggregation one eventually arrives at the macro level, whereby the whole societal system is the subject of investigation. If one follows the argumentation of TOL (2005) and FANKHAUSER (2009),

who reject a joint analysis of adaptation and mitigation (cf. No. 18), then optimality refers exclusively to the **intensity of adaptation of the societal system**. Hence, based on benefit-cost considerations, the task is to examine how much resources should be channelled into the adaptation of society. If, however, one follows the exception established by TOL (2005) and focuses on the so-called "facilitative adaptation", which should be understood as building adaptive capacity (No. 18), then the aim is to determine the **optimal combination of adaptation and mitigation intensity** and the allocation of resources that goes along with it. In the following an attempt is made to organise the scientific papers, as far as possible, according to this framework.

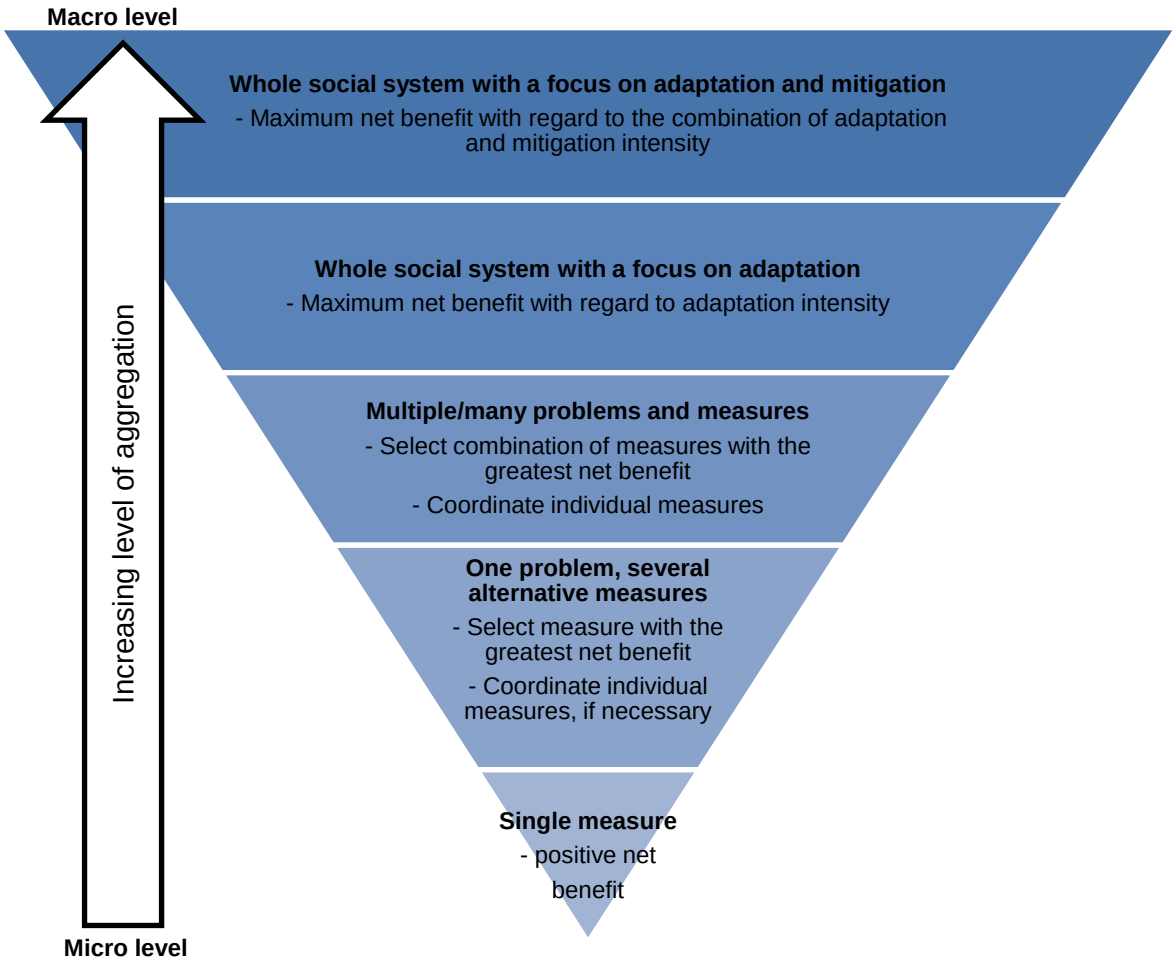

Figure 3: Dimensions of Optimal Adaptation

3.1.1 Theoretical foundations

24. The literature on the theoretical foundations of optimal adaptation is subdivided into **two strands**. The first strand (Section 3.1.1.1) examines the problem on the basis of an **isolated assessment of adaptation** and therefore follows the line of reasoning presented in TOL (2005), according to which adaptation and mitigation demonstrate different dimensions and scales and hence have to be examined separately (No. 18). The second strand (Section 3.1.1.2) undertakes an **integrated assessment of adaptation and mitigation** and thus re-

sists this logic and/or refers (implicitly) to the exceptional case of building adaptive capacity set out by TOL (2005).

3.1.1.1 Isolated assessment of adaptation

25. The criterion of optimality can on the one hand apply to the **design** and **intensity** (static analysis, No. 26-29) or on the other hand to the **timing** or **intertemporal allocation** of adaptation (dynamic analysis, No. 30-33). In this context MENDELSOHN (2000) and ADGER et al. (2005) emphasize that a static analysis is sufficient for sectors which adapt rapidly due to a low capital intensity, whereas for capital-intensive, rigid sectors a dynamic analysis is essential.

26. **Static considerations** of optimal adaptation **are based on formal, microeconomics approaches**. The fundamental approach is supplied by MENDELSOHN (2000), who examines optimal adaptation intensity in a simple, deterministic optimisation model, whereby a distinction is made between private and joint adaptation. In the case of private adaptation, the actor who implements the adaptation measure is the only one who derives a benefit from it. The optimal adaptation intensity maximises the net benefit of the actor, that is, it brings the marginal utility and the marginal costs of adaptation into balance. **Joint adaptation** is distinguished by the fact that each of the individually performed adaptation efforts influences the utility levels of multiple actors, i.e. the adaptation displays the characteristics of a public or club good. As a result, the optimal adaptation intensity is determined according to SAMUELSON'S rule (1954), according to which the sum of the marginal utilities of all affected individuals (vertical aggregation of the willingness-to-pay curves) must equal the marginal costs of adaptation.

27. Based on this fundamental analysis the following works address **questions of a more specific nature**: EISENACK (2009) considers a **stochastic partial market model** in which the firms can avert the negative impacts of extreme weather events on their production through private adaptation. EISENACK (2010) generalises this model by allowing not just two different, but a continuum of, weather conditions. LEE and THORNSBURY (2010) also focus on a similar problem: They examine the optimal level of adaptation for (agricultural) firms in the context of a **two-stage game**, whereby in the first stage they define the area under cultivation, and in the second stage they decide about the level of adaptation investment, by which they can influence the variability of the (climate change-induced) stochastic crop yields.

28. In addition to the formal approaches just introduced, a number of individual works also exist whose line of argumentation is likewise based on **microeconomic considerations**, but which are conducted on a purely **qualitative level**, i.e. without the aid of models. DANNENBERG et al. (2009) and OSBERGHAUS et al. (2010a) further develop the aspect of the optimal collective adaptation. Like ADGER et al. (2005), they also stress the need to consider potential **externalities** between the individual adaptation measures in their optimal design. ADGER et al. (2005) also call for the consideration of **transaction costs**, the costs of inaccurate prediction and values not determined by market mechanisms within benefit-cost analyses. FÜSSEL (2007) reveals fundamental relationships between climate change-induced **risks** and optimal adaptation: He states that as the knowledge of the aforementioned risks and their

future development increases, more specific problem-focussed adaptation measures are beneficial with regard to the optimality criterion. Given a lower level of knowledge, on the other hand, measures for building adaptive capacity are preferable. Furthermore, the author regards experience in dealing with specific risks as a significant determinant of adaptive capacity – a lower level of experience should be compensated with greater capacity. The efficiency of adaptation measures targeted at current major risks is only given in the medium- to long-term if future climatic changes are taken into account when designing these measures. Finally, it has to be taken into account that, where no-regret or low-regret measures exist (i.e. measures which, under all plausible climate scenarios, demonstrate positive or only slightly negative net benefits), the optimal planned adaptation does not necessarily require accurate projections of climate change and its impacts.

29. **Macroeconomic approaches** play a secondary role in the research on isolated static adaptation optimality. Of note here is the work of AAHEIM et al. (2009), which uses a **computable general equilibrium model** with multiple sectors and regions. The adaptation occurs directly via shifts in technologies and preferences and indirectly via the corresponding market reactions. By comparing equilibria with varying levels of adaptation (and the respective exogenously given mitigation), conclusions about the macro-economically optimal adaptation strategy are drawn.

30. **Microeconomic approaches** also dominate in the **dynamic analysis**. FANKHAUSER et al. (1999) use a simple model to formalise the conditions for the **optimal timing** of an adaptation investment. The basic trade-off when setting the timing for the investment is explained as follows: A delay in the investment initially leads to saved adaptation costs which, however (in the case of exogenous mitigation), are offset by additional damage costs in the future. In this context, FANKHAUSER (2009) identifies three fundamental **determinants of optimal adaptation timing**: the change in the adaptation costs as time passes, possible short-term, transient advantages of the adaptation as well as long-term irreversibilities.

31. DANNENBERG et al. (2009), DOBES (2010), and OSBERGHAUS et al. (2010a) point out that the described trade-off above (No. 30) is actually much more complex in view of massive **uncertainties** about the consequences of climate change and potentially **irreversible investments**. As originally described in the **option value theory** of DIXIT and PINDYK (1994), the prospect of **learning** or gaining new information about the extent of climate change now favours the stalling of investment. The benefit expected to result from this –the option value – is, of course, to be included in the benefit-cost calculation on the investment decision. Using a formal option value model WRIGHT and ERICKSON (2003) examine optimal adaptation timing under the restriction that **no perfect foresight** is given on the part of the actors. In concrete terms, temperature development, which influences the net benefit of the adaptation investment, is modelled as a dynamic stochastic process.

32. Another also largely microeconomics-oriented branch of the literature deals less with the optimal timing of adaptation investments than with the problem of how **the intertemporal allocation** of adaptation measures and/or the accumulation of adaptation capital should best be designed. The question here is basically how much resources should be channelled into **anticipatory** adaptation measures and how much in measures that **react** to climate change impacts that have already occurred (cf. e.g. FANKHAUSER et al., 1999, MENDELSOHN, 2000).

CALLAWAY (2004) develops a general modelling approach for analysing the optimal intertemporal adaptation of an actor (e.g. a firm or country) to **climate variability** or to the i**mpacts of climate change**. Adaptation can be undertaken in the short term via management inputs or over the long term via capital stock. FANKHAUSER et al. (1999) argue that in view of the uncertain and changing climate conditions, (adaptation) **capital** should either be more **rapidly offset** and exchanged or it should be assigned greater robustness and flexibility – which of these two alternative is preferable depends on their relative costs. FISHER and RUBIO (1997) study the special case of the **optimal intertemporal water storage capacity** of a region. The supply of water to the reservoir is modelled as a stochastic value, the variability of which grows with increasing intensity of climate change. It is also taken into consideration that the building of capacity can be accompanied by negative environmental externalities.

33. Finally, DUMAS and HA-DUONG (2008) undertake the only attempt so far to address the problem of the optimal intertemporal allocation of adaptation using a **macroeconomic approach**. In the framework of a **growth model** with perfect information and foresight of the actors, and omitting the mitigation option, they determine the **optimal adaptation investment path** and analyse the relationship between the optimal amortisation rate and the speed of climate change.

3.1.1.2 Integrated assessment of adaptation and mitigation

34. Analogous to the isolated assessment of optimal adaptation (Section 3.1.1.1), the integrated assessment of adaptation and mitigation is also broken down into **static** (No. 35-38) and **dynamic** components (No. 39-45).

35. The starting point for this analysis is given by a number of works which discuss, without any model-theoretical support, **the fundamental significance and the relationship between adaptation and mitigation** for climate policy while neglecting the dynamic or intertemporal aspects of the problem. There is broad agreement in the literature that an economically meaningful climate policy which minimises the total costs of climate change must necessarily encompass both mitigation and adaptation components (e.g. BARDT, 2005, IPCC, 2007a and PIELKE, 2007). Also, the two strategies are essentially **substitutable** to some extent (BMF, 2010, and FANKHAUSER, 2009).

36. TOL (2005) outlines the **basic static marginal condition** that characterises the optimal combination of adaptation and mitigation[6] – under the condition (No. 18) put forward by TOL (2005) and KLEIN et al. (2005) that only adaptation in the sense of building adaptive capacity is comparable with mitigation. Furthermore, when determining the optimal mix it has to be taken into account that interdependencies, more specifically **synergies or conflicts**, may exist between certain adaptation measures and emissions reduction. DANG et al. (2003) demonstrate this using Vietnam as an example; ROSENZWEIG and TUBIELLO (2007) carry out a corresponding study for the agricultural sector. KLEIN et al. (2005) caution against placing

[6] This condition states that the marginal costs of mitigation have to brought into balance with the marginal utility of mitigation. The latter arises from the compensation of the residual marginal damage costs and the marginal costs of the adaptation.

the focus on potential synergies when designing the adaptation-mitigation mix and thereby losing sight of the optimality criterion.

37. Besides these general considerations, some individual works explore more **specific aspects** of the optimal relationship between adaptation and mitigation on the basis of **microeconomic models**. In their paper, MCKITRICK and COLLINGE (2002) question the existence of an unambiguously optimal level of emissions or an **unambiguously optimal environmental policy** against the background of adaptation and/or **defence measures** of (potentially) damaged actors. They demonstrate that, due to the non-convexities caused by the adaptive behaviour, this is not necessarily the case. In the second step of their analysis they derive a formal condition for the existence of an unambiguous optimum.

38. KANE and SHOGREN (2000) approach the topic of optimal climate policy using the **theory of endogenous risk**, i.e. they consider a country (mitigation efforts of the rest of the world are given) which can influence its own climate change-induced damage risk by selecting its own adaptation and mitigation efforts. In the process, the authors characterise the optimal adaptation-mitigation mix and determine how this must be adjusted if there is an exogenous increase in the damage risk. The basic approach of this paper goes back to the insurance theory model of EHRLICH and BECKER (1972) in which, detached from the context of climate, they examine the trade-off between "self-protection" (lowering damage probability – mitigation) and "self-insurance" (lowering the residual damage – adaptation). TULKENS and STEENBERGHE (2009) as well as AUERSWALD et al. (2011) investigate the adaptation-mitigation mix within the framework of similar models, but under the condition of an **exogenous risk of damage**.

39. In the **dynamic analysis** of the optimal adaptation-mitigation mix only a few **microeconomic approaches** are to be found. The Scientific Advisory Board of the German Federal Ministry of Finance (BMF) argues that, given the uncertain consequences of climate change and potential irreversibilities, **adaptation** displays an **optional character** (BMF, 2010): In principle, in the light of benefit-cost considerations, delaying adaptation would be desirable in order to reduce the massive uncertainty surrounding the impacts of climate change through additional information or learning; however, the situation is complicated by the well-known problem of irreversibility. The adaptation option alleviates this problem, since it can mitigate potential negative impacts, even at a later point in the future, thus providing scope for manoeuvre for the above-described waiting strategy. INGHAM et al. (2007) analyse this problem in a **stochastic two-period partial market model** and come to the conclusion that the prospect of learning or information gain in conjunction with the adaptation option causes a lower optimal level of mitigation in the present. ATHANASSOGLOU and XEPAPADEAS (2011) consider a dynamic problem where the decision maker invests in an anticipatory adaptation technology at time zero and subsequently determines the optimal mitigation path. The optimal investment intensity grows with the level of uncertainty. Provided the adaptation costs are sufficiently low, adaptation and mitigation demonstrate a substitutive relationship, and otherwise a complementary relationship. INGHAM et al. (2005) provide a broad overview of the literature on the role of uncertainty, irreversibility and learning in climate policy, which however goes far beyond the scope of this report.

40. The above (No. 38) introduced static **endogenous risk approach** of KANE and SHOGREN (2000) is **embedded in a dynamic context** by LECOCQ and SHALIZI (2007) and expanded in a number of aspects such as e.g. the explicit differentiation between anticipatory and reactive adaptation, the introduction of different sectors and regions and the uncertainty about the distribution of environmental damages. BERGER (2011) also expands the contribution by KANE and SHOGREN (2000). First, he models a decision-making situation that extends over two periods in order to consider the investment character of adaptation and mitigation (investment in the adaptation and/or mitigation in the first period, occurrence of the damage in the second period). Second, he illustrates the massive uncertainties with regard to the impacts of climate change by assuming that the probabilities for the occurrence and extent of the damage are unknown or ambiguous for the decision maker, whereby the decision maker displays **ambiguity aversion**. Lastly, TULKENS and STEENBERGHE (2009) deliver a dynamic version of their static model (No. 38).

41. The following works are based on classical **macroeconomic modelling approaches**: AALBERS (2009) uses a dynamic stochastic general equilibrium model to calculate the **optimal discount rates** for adaptation and mitigation investments and other investments. He demonstrates that these generally differ since the two investment types are exposed to different degrees of climate-related and non-climate-related risks. BRÉCHET et al. (2010) examine the **optimal accumulation** of physical capital, adaptation capital and greenhouse gases in a deterministic Solow-Swan growth model with one sector. In doing so, they establish a correlation between the optimal adaptation-mitigation ratio and productivity. CHISARI (2010) also deals with the optimal adaptation and mitigation path. However, he uses his growth model to reproduce stochastic **catastrophes** or **negative growth shocks** that could be brought about by climate change.

42. **Integrated Assessment Models (IAMs)** dominate in the dynamic analysis of the optimal adaptation-mitigation mix.[7] These numeric models combine knowledge from a range of disciplines in order to gain insights relevant to policy (PATT et al., 2010). IAMs are also used – in relation to specific countries or regions – to estimate the benefit and costs of adaptation (No. 46). In the climate context, physical climate models which illustrate the cause and effect chain of climate change are typically coupled with economic growth models. Having long been limited to mitigation, individual attempts have been made to depict the **adaptation option implicitly** using IAMs. Based on the so-called Ricardian approach, adaptation is modelled as a shift in production (in relation to goods, sectors or regions). As IAMs of this type are only of secondary importance, they will not be addressed further in this report (see PATT et al. (2010) for more information).

43. The **latest generation of IAMs** treat adaptation as an explicit control variable. The general focus of this model class is on the **optimal intra- as well as inter-temporal adaptation-mitigation mix**. The individual works set different priorities:[8] DE BRUIN et al. (2009a) are the

[7] IAMs can be used not only to determine the optimal combination of adaptation and mitigation but also to calculate the combination of measures that guarantees the realisation of a given warming or emissions target at the lowest possible costs (AGRAWALA et al., 2011, see also No. 62).

[8] The following IAMs are mainly applied here: AD-WITCH, AD-DICE, AD-RICE and FUND. A description and a comparison of the various model types would exceed the scope of this report. For further information see AGRAWALA et al. (2011), PATT et. al (2010) or BOSELLO et al. (2010).

first to model adaptation explicitly and they go on to generalise their analysis in a second step by considering **regional differences in climate damages** (DE BRUIN et al., 2009b). DE BRUIN et al. (2009d) as well as DE BRUIN and DELLINK (2009) test for both variants of the model to what extent **suboptimal levels of adaptation** can be compensated by changes in the mitigation activity. Within a model of multiple regions, AGRAWALA et al. (2009) make a distinction between **anticipatory adaptation** in the sense of building adaptive capacity and **reactive adaption**. The result is a broader optimal inter- and intra-temporal climate policy mix which comprises not only adaptation and mitigation, but also the two alternative forms of adaptation. BOSELLO et al. (2010) complement this approach by modelling **stochastic catastrophic events**. In BOSELLO et al. (2009), the role of the markets and price signals in the distribution of adaptation measures are at the centre of attention. BOSELLO (2010) expands the analysis of the optimal adaptation-mitigation mix by allowing **investment in research and development** as an additional option in climate policy. In their model, BOSELLO and CHEN (2010) consider two **different forms of uncertainty**, on the one hand uncertainty about catastrophic events, and on the other hand, uncertainty about the **distribution** of the damages induced by these events. Lastly, TOL (2007) explores the trade-off between adaptation and mitigation, specifically in relation to the problem of sea-level rise.

44. AGRAWALA et al. (2011) summarise the **key findings** that have been found to be robust across the different types of IAM. Various model calculations underpin the **strategic complementarity** of **adaptation and mitigation**. Since both strategies reduce the (residual) damages of climate change, the calculations replicate the theoretical result according to which two instruments that pursue the same goal cannot do worse than a single instrument. In fact, it has been demonstrated that welfare can be increased if the adaptation option is applied in addition to the mitigation option (cf. e.g. DE BRUIN et al., 2009a or BAHN et al., 2010). In this context **adaptation** turns out to be the **favoured option** in which more resources are invested than in mitigation and which also makes the greater contribution to damage reduction (BOSELLO et al., 2010). However, this result is largely due to the fact that the possibility of catastrophic events which have a very low likelihood of occurence and which can only be avoided through mitigation cannot be modelled in the IAMs (SETTLE et al., 2007). Despite the strategic complementarity, there is a **trade-off between adaptation and mitigation**, since both are competing for scarce resources (HOF et al., 2009). Furthermore, expansion of the adaptation diminishes the marginal utility of mitigation, and vice versa (FANKHAUSER, 2010). The reciprocal crowding-out of both strategies is however characterised by **asymmetry**: adaptation displaces mitigation to a greater degree than in the reverse situation because in the medium to long term the extent of the damage avoided by mitigation is too small to reduce the need for adaption. With regard to the **optimal timing** of both strategies, the following rule has emerged: Whereas investment in mitigation should be made as early as possible, adaptation expenditures should follow the dynamic of the expected climate damages, i.e. they should occur at first with a certain time lag, but thereafter the rate of spending should increase. This discrepancy is plainly attributable to the respective intertemporal distribution of the costs and benefits of the two options. An **increase in climate change-induced damage** implies a higher optimal level for both adaptation and mitigation. However the implications of this in terms of the optimal mix are ambivalent. They depend on whether the adaptation is modelled as a stock variable (greater share of the damage reduction through adaptation, BOSELLO et al., 2010) or as a flow variable (greater share of the damage reduction through mitigation, DE BRUIN et al., 2009). Finally, with regard to the **re-**

gional dimension of adaptation, it can be stated that adaptation expenditures are concentrated in the developing countries because these are far more vulnerable than industrial countries. Significant differences are also reported with regard to the form of adaptation. While non-OECD countries take proactive and reactive adaptation measures in equal proportion, most measures taken by the OECD countries are of a proactive nature (BOSELLO et al., 2010 put the share at 88%).

45. Referring to these approaches, several critical opinions have been put forward in the literature that question the **validity and political relevance of IAMs** and point out their limitations (e.g. JOTZO, 2010, or FANKHAUSER, 2009). The basic tenor is that IAMs are insufficient to take the heterogeneous and diffuse character of adaptation into account and are therefore unsuitable for delivering concrete policy recommendations. At best, qualitative insights into the relationship between adaptation and mitigation can be expected. In their key contribution to the discussion, PATT et al., 2010 argue that many of the characteristic features of adaptation can only be reproduced insufficiently in IAMs. As a result, the model calculations tend to **overestimate the net benefit of adaptation** and propagate insufficient mitigation efforts. Specifically, the authors put forward the following points of criticism: IAMs are not capable of reflecting the **bottom-up character of adaptation**. This is demonstrated by the fact that the costs and the benefits of adaptation are linked to local measures and born by, or are of benefit to, local stakeholders (see also TOL, 2005). Statements on the optimal level and distribution of adaptation expenditures therefore require knowledge of the respective local circumstances. IAMs with a global focus, most of which work with a single damage cost function, cannot however meet these requirements. Most IAMs are based on the assumption that a **certain part of the adaptation** takes place **autonomously and proportionally to the occurring damages**, whereby these are modelled as a function of the global average temperature. However, adaptation is usually performed on the basis of perceived risks with regard to extreme weather events or experience in relation to altered climatic conditions (THOMAS et al., 2007), neither of which are necessarily a linear function of the global average temperature (EMANUEL, 2005). Evaluating climate change impacts that are not determined by the market mechanism also proves problematic. Even though the first relevant studies on the benefits of mitigation, e.g. prevented biodiversity loss (IPCC, 2007a), do make it possible to draw conclusions about non-monetary benefits of adaptation, the problem of evaluating **non-monetary adaptation costs** remains unsolved, since these costs are primarily incurred at local level and are therefore difficult to consider adequately in IAMs. The underlying assumption of optimal autonomous adaptation in IAMs implies that the **actors** make the best possible use of the adaptation-relevant information available to them (e.g. climate predictions), i.e. they **maximise the value of the information**. However this means that huge demands are placed on the information processing capacity of the actors, which cannot realistically be met (IPCC, 2007a). Other behavioural obstacles also argue against the best possible use of information (see No. 78). **Modelling uncertainty** is another problem that is difficult to solve. This applies in particular to adaptation, since it is primarily tied to the spatial and temporal distribution of climate change impacts. This difficulty is compounded in turn by potential behavioural obstacles of the actors in handling these uncertainties (see No. 77).

3.1.2 Empirical determination of the benefits and costs of adaptation

46. An empirical determination of the benefits and costs of adaptation measures is the prerequisite for the actual implementation of optimal adaptation (mitigation) strategies (No. 23). Cost and benefit data not only form the basis for project-related decision-making at regional or local level, they also serve as a price signal for politicians at international level, especially when it comes to the financing of adaptation measures (OECD, 2008). With regard to the collection of regional and/or local benefit and cost data, a distinction is made between two fundamental approaches (GEBHARDT et al., 2011, cf. Figure 4). The starting point for the **bottom-up approach** is formed by climate projections and estimates of climate change impacts for the region of interest. Based on this, and with the involvement of decision makers and stakeholders, appropriate adaptation measures tailored to the regional (or local) context are identified and ultimately subjected to economic assessement. In contrast, **top-down approaches** are aimed at breaking down global, Integrated Assessment Model-based benefit and cost estimates to the regional or local level by so-called dynamic downscaling (cf. e.g. KEMFERT, 2008).

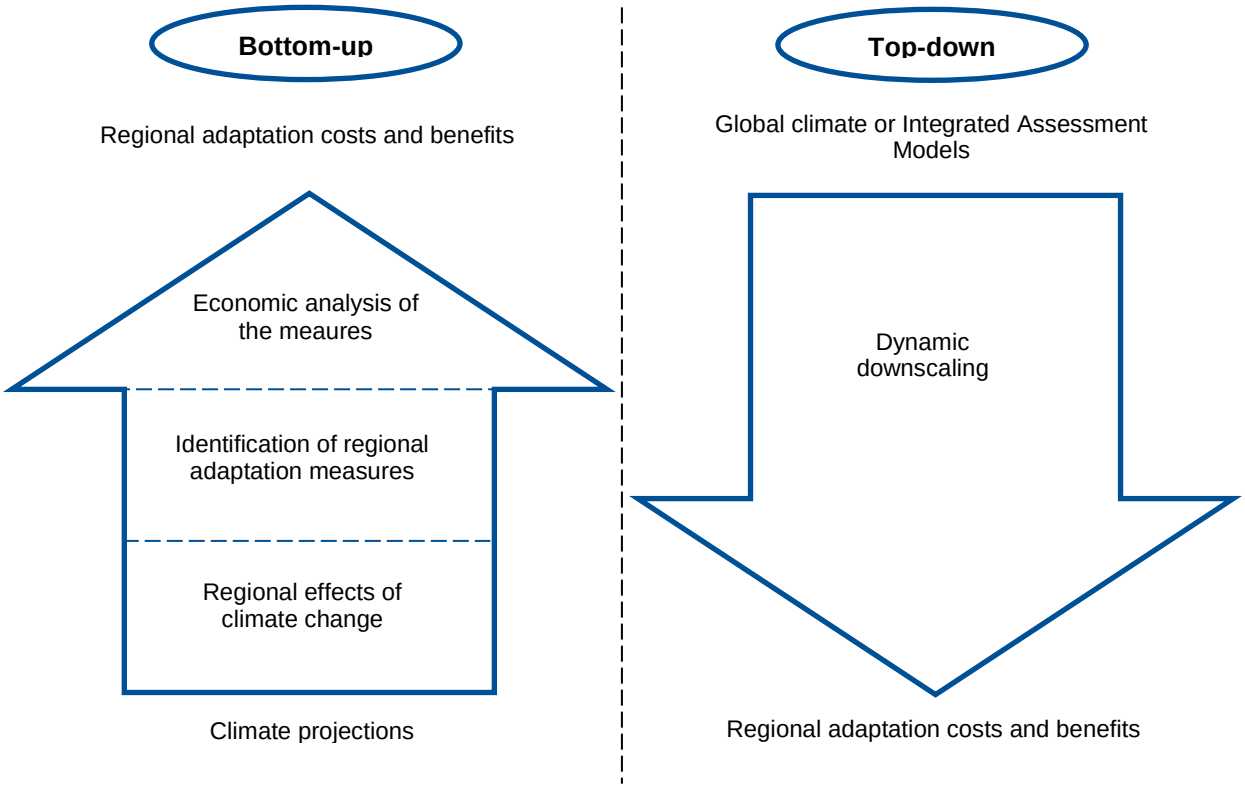

Figure 4: Two ways to determine the regional costs and benefits of adaptation

47. Due to massive uncertainties about climate change impacts as well as methodological problems related to the evaluation of non-monetary goods (e.g. the recovery function of a landscape) the benefit of adaptation is not easy to record or quantify (see also No. 62). It is not surprising therefore that a significantly smaller proportion of the relevant contributions deal with the **benefit side**. DOBES (2009) draws up a **multi-stage plan for identifying the priorities and preferences** of individuals with regard to adaptation measures, which can be

regarded as the first step towards a monetary evaluation of benefit. GLENK and FISCHER (2010) examine the general public's evaluation of government-implemented adaptation measures. At the centre of their study is the question of how **preferences** for the said measures are **constituted** by hierarchical networks of values and convictions. The authors address this question by evaluating a survey of the population using econometric methods. They come to the conclusion that constitutive values such as efficiency, sustainability or solidarity are more robust evaluation criteria than the marginal willingness-to-pay, especially where long-term project are concerned.

48. CHAMBWERA and STAGE (2010) develop a **conceptual framework** that can be used to determine the benefits and costs of adaptation in developing countries. The result is a catalogue of criteria that has to be gone through when collecting data. MARGULIS et al. (2008) also perform an **integrated assessment of the benefit and cost side**. They present a **top-down approach** to implementing adaptation measures. They break climate projections down to the regional or local level on the basis of an impact assessment model and then, taking budget restrictions into account, they perform a benefit-cost analysis. PRC (2009) deals with the fundamental methodological issues of benefit-cost analysis with reference to the example of adaptation measures concerning European coastal protection. TRÖLTZSCH et al. (2011) give an overview of (primarily bottom-up-based) applied studies on the benefits and costs of adaptation measures across the different sectors and fields of activity in Germany.

49. The following studies focus exclusively on the **cost side** and in doing so follow the top-down approach: DESCHENES and GREENSTONE (2007) demonstrate how adaptation costs in the health sector can be estimated using **physical climate models, health economics models and econometric methods**. The WORLD BANK (2010c) estimates adaptation costs for developing countries by means of climate model projections; the secretariat of the United Nations Framework Convention on Climate Change forecasts adaptation costs or adaptation investments using the **OECD ENV-Linkages Model** (UNFCCC, 2007). OSBERGHAUS and REIF (2010) make the first attempt to examine the **fiscal impact** of adaptation measures and use a comprehensive collection of theoretical concepts and econometric methods to do so.

50. Several studies **criticise the top-down-based cost estimates**. FANKHAUSER (2010) identifies the (methodological) weaknesses of previous adaptation cost estimates. He finds fault with, among other things, the breadth and depth of the studies as well as the omission of relevant costs – most studies capture the investment costs only and not the total lifetime costs of the respective measure. The European Environment Agency (EEA, 2007) and PARRY et al. (2007) each give a review of this subject matter, whereby however the latter contribution focuses on **sector-specific conditions**.

51. The study by GEBHARDT et al. (2011) takes up on this criticism: Taking the state of Saxony-Anhalt as an example, the study describes a first attempt to develop and elaborate a **bottom-up approach** in a regional context as an innovative method in the research on the economics of adaptation. The resulting consideration of specific regional conditions allows a more precise and detailed illustration of the adaptation costs relevant for regional or local decision makers (see also GEBHARDT and HANSJÜRGENS, 2011). In connection with the bottom-up approach, PATT and SIEBENHÜHNER (2005) discuss the potential contribution of **agent-based models** (ABMs) to the empirical determination of adaptation costs. The basic

idea here is that, given their capacity to reproduce and analyse complex adaptive systems, ABMs can deliver information and findings relevant for the determination of adaptation costs.

3.2 Non-efficiency-related goals

52. In addition to optimality or efficiency, **(distributive) justice, sustainable development** or **ecological criteria** and **security of supply,** in particular, are cited in the relevant literature as objectives to be considered in the context of adaptation measures (cf. e.g. FANKHAUSER, 1999, IPCC, 2001, KLEIN et al., 2005, DANNENBERG et al., 2009, OSBERGHAUS et al., 2010a). RYNIKIEWCZ and CHETAILLE (2006) highlight the importance of the equity goal in connection with sustainable development aimed at reducing poverty in developing countries. TOL (2007) shows that adaptation measures can also benefit **security policy goals**, at least indirectly in that, for instance, migration movements or scarcity of resources can be counteracted or controlled, thus avoiding violent conflicts. Chiefly the aspects of equity, sustainable development and security of supply are enlarged upon in the literature (see No. 53-55).

53. DANNENBERG et al. (2009) and OSBERGHAUS et al. (2009) differentiate between **vertical and horizontal equity**. The former concerns the fair treatment of individuals with different levels of income. In the context of adaptation this implies, above all, ensuring that low-income individuals are also able to implement the necessary adaptation measures. Horizontal equity refers to the equal treatment of all individuals before and under the law. This aspect becomes particularly relevant when it comes to implementing government adaptation measures, e.g. in cases where the implementation of flood control measures makes sense in terms of efficiency for one region, but not for another. GEMENNE (2009) differentiates between **distributive** and **retributive justice**, which, following the polluter-pays principle, demands that the cost of the adaptation measure be borne by those responsible for inducing the climate change. Following on from this, other authors call for a greater emphasis to be put on adaptation costs, in addition to damage costs, in the course of **international burden-sharing** in relation to climate change impacts (GTZ, 2007 and EISENACK, 2011). In this context, referring to deontology, consequentialism and solidarity, DELLINK et al. (2009) develop **principles for fair distribution of the burden**, and operationalise these principles for implementation into policy practice. DULAL et al. (2009) also establish **operationalisable dimensions of equity**, among others, the fair or equal treatment of the population in the context of government-initiated adaptation measures or equal right of access to government-created adaptation goods. Furthermore, for different areas of activity, e.g. mobility or living, they exemplarily demonstrate how equity goals can be integrated into adaptation planning. PAAVOLA and ADGER (2002) create a **conceptual framework** for analysing questions of equity in the context of adaptation that they base on a broader definition of equity, which includes values such as human life or health, or the long-term integrity of the Earth.

54. In the branch of the literature discussed here, great weight is attached to the question of how adaptation measures can be reconciled with the goal of **sustainable development**, particularly in relation to emerging and developing economies. GOKLANY (2007) identifies **joint determinants of success** for mitigation, adaptation and sustainable development, which serve as an orientation aid for the implementation of suitable strategies. GTZ (2007)

and FANKHAUSER (2009) address possible **synergies** between adaptation and development measures. DANG et al. (2003) approach this topic on the basis of a **case study** for Vietnam.

55. DANNENBERG et al. (2009) and OSBERGHAUS et al. (2010a) draw attention to the special significance of **security of supply** in the context of adaptation. They take the energy or agricultural sectors as examples where, without appropriate adaptation measures, it cannot be guaranteed that the demand will be satisfied constantly and sufficiently. In a **partial equilibrium model of the agricultural sector** that is coupled with a general equilibrium model encompassing several factor markets, CALZADILLA et al. (2009) examine the implications of different adaptation measures with regard to the security of supply. This same question is taken up by FINGER and SCHMID (2007), who combine for this purpose a **biophysical model** (simulation of the relationship between climate and planting or plant growth) with an economic model (simulation of private adaptation by farmers). ROSENZWEIG and TUBIELLO (2007) discuss adaptation-related challenges that arise in relation to security of supply in the **agricultural sector**.

3.3 Evaluation and choice of adaptation measures

56. The realisation of one or more of the objectives mentioned in the previous sections first requires an evaluation of the available adaptation options on the basis of specific criteria. Building on this first step, the selection of options can be carried out using appropriate methods. Which **criteria** should be applied **to evaluate the measures** depends on the respective form of the adaptation (SMIT et al., 2000, cf. Figure 5). In this context, on the one hand **spontaneous (mostly also autonomous and reactive) adaptation measures** must be distinguished. These occur exclusively with the original intention of adaptation to (at a later stage) alleviate climate change-induced damages or to make use of opportunities to do so. However, additional goals such as optimality or equity are naturally not systematically pursued here. Therefore an evaluation according to the achievement of these goals would not be appropriate. Instead in the relevant literature spontaneous adaptation is primarily evaluated in relation to its cost-benefit ratio, i.e. the damage savings potential (or potential gains) are compared with the costs of the adaptation measures. Estimates of this type are usually carried out within the framework of Integrated Assessment Models or Impact Models (TOL et al., 1998). The results of the evaluation are not only relevant in order to be able to better predict the impacts of climate change; they are also a necessary precondition for modelling reference scenarios which are free of political interventions and serve as a basis for developing adaptation policies (SMIT et al., 2000).

57. In contrast to spontaneous adaptation, for **planned (mostly also government-induced, anticipatory)**[9] **adaptation measures** numerous evaluation criteria are used (e.g. SMIT et al., 1999). The Intergovernmental Panel on Climate Change has put forward fundamental preliminary considerations on the selection of these criteria (IPCC, 1994). In particular, it stresses that the criteria must be as specific as possible and clearly verifiable. The most elementary criterion is **effectiveness**, i.e. the degree to which the goals of the measure are achieved

[9] The criteria listed in the following are mostly associated in the literature with government-implemented, planned adaptation measures. Nevertheless, they can also be applied to private, planned measures, especially when determining whether they require corrective action by the government (see Chapter 4).

(CIMATO and MULLAN, 2010). If only one goal is pursued, then the application of the effectiveness criterion is trivial. In the practice of adaptation policy, however, the aim usually is to simultaneously achieve several goals, which frequently exhibit conflicting relationships (KLEIN et al., 2005), so that the clarity of the effectiveness criterion is lost. This necessitates a weighting or ranking of the individual goals, based on which trade-offs between the goals can be compared and the adaptation options can be selected according to specific methods (see No. 60) (IPCC, 1994). The goal of optimality is afforded special significance in relation to the effectiveness criterion insofar as no different goal achievement levels exist, i.e. the (selected) adaptation or allocation measure is either optimal or not.

58. The criterion of **cost-efficiency**, in analogy to the standard price approach, is aimed at achieving a politically defined goal or an adaptation goal emerging from technical or scientific premises at minimal social cost (cf. e.g. SMIT et al., 1999 and 2000 as well as SHARMA and SHARMA, 2010). In contrast to optimality, the benefit of adaptation is explicitly not taken into account in order to avoid the associated information problems. Several studies deal with the operationalisation of the cost-efficiency criterion in the context of various fields of activity. WHEELER (2011) develops a **quantitative method**, which supports decision makers and/or donor countries in determining the cost-efficient allocation of adaptation resources in developing countries. This study focuses on the problem areas of weather-induced catastrophes, sea-level rise and agricultural production. CAI et al. (2011a) design a **simulation model** for defining cost-efficient adaptation strategies in the **energy sector**. Within this framework multiple energy sources, technologies and subsectors can be observed. Furthermore, the model allows the consideration of uncertainties on different levels, e.g. in relation to climate change impacts or adaptation planning. The model is applied in the context of a regional case study (CAI et al., 2011b).

59. In addition to the central criteria of effectiveness and cost-efficiency, a range of complementary and/or alternative criteria are introduced. SMIT et al. (1999) and TOL (1996) stress that the **implementability** or the political enforceability of measures as well as their **acceptability** among the general public determine the success of the adaptation. SMITH (1997) and SMITH and LENHART (1996) argue that, in view of the uncertainty surrounding the impacts of climate change, measures should be designed to be as **flexible** as possible, i.e. they should be adjustable to altered climatic conditions at short notice or be able to react to unexpected (extreme) events. Another criterion which takes uncertainty into account is the **robustness** of the measures. This demands that the effect and functionality of the measures be guaranteed for the entire range of possible and/or probable climatic conditions (LEMPERT and SCHLESINGER, 2000). The **no-regret criterion** links the criteria of optimality and robustness. Accordingly, measures should generate a non-negative net benefit under all possible climate scenarios (HALLEGATTE, 2009). Finally, on the basis of the criteria mentioned above, the selection of the proposed adaptation measures is undertaken using specific methods (see the following sections). Moreover, these criteria provide pointers for the design of (planned) adaptation measures and strategies for policy-makers (SMIT et al., 2000).

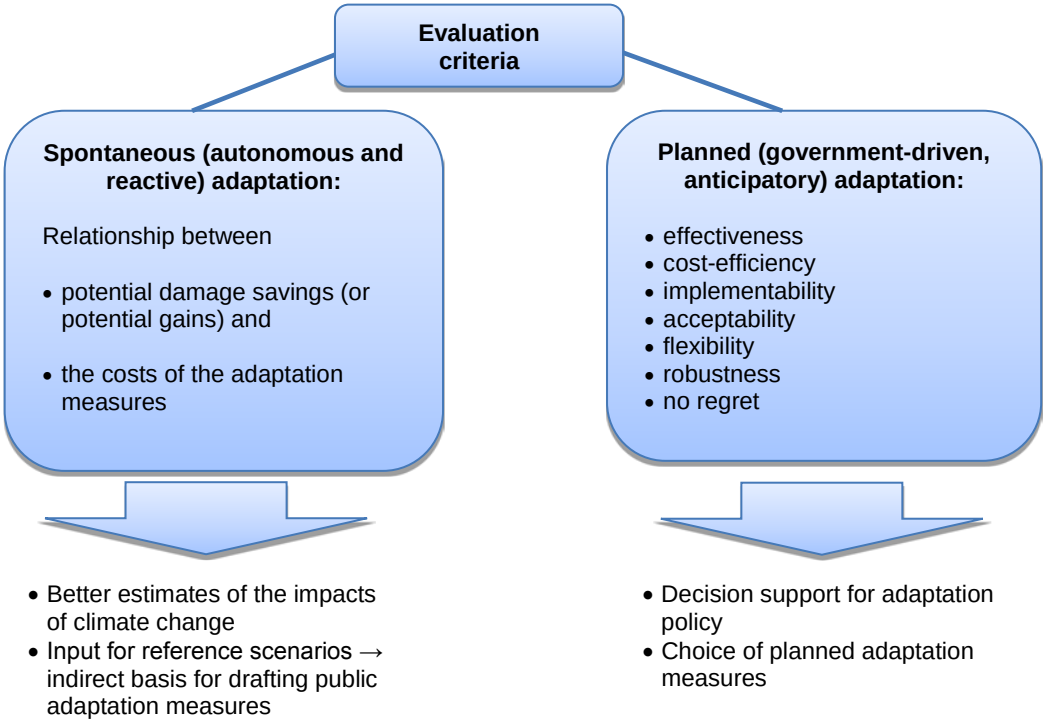

Figure 5: Criteria for evaluating adaptation measures

60. On the basis of the evaluation criteria for planned adaptation measures summarised in Figure 5, the respective decision maker now has to select the "best" measure or the "best" set of measures. If only one goal is being pursued and no other criteria are to be applied, e.g. flexibility, then the selection can simply be made using the criterion of effectiveness. However as soon as multiple goals are to be realised and/or additional criteria are to be used, a special **selection procedure** has to be implemented. The Intergovernmental Panel on Climate Change provides a comprehensive summary of these procedures (IPCC, 2001a),[10] the essential concept of which is concisely illustrated in Table 4 along with a brief evaluation. Here a distinction is made between procedures that contribute **directly to the decision-making process**, in other words, those that result in the generation of an explicit ranking of the possible courses of action. On the other hand, procedures exist which only **support the decision maker indirectly**, by clarifying the implications and trade-offs between the options or by narrowing down the number of options that come into question. However they do not produce any clear recommendations for action.

61. Procedures belonging to the first of the above-mentioned groups are all – with the exception of game theory (No. 64) – part of **decision theory**. This is aimed at helping decision makers to arrive at the "best" choice, from their perspective, from a range of possible courses of action. Using quantitative methods, each individual option is assigned a certain value

[10] Although the said source refers to the mitigation context, the procedures described therein can be similarly applied within the framework of adaptation decisions.

based on the respective form of the (quantitative and/or qualitative) evaluation criteria, and this provides the basis for ranking the various options. Model-based tools are frequently applied for this purpose as part of an interactive framework within which the decision makers structure the problem and disclose their preferences. In addition to identifying the "best" choice, the relevant procedures are applied to analyse the decision situation and, where applicable, to reveal a better course of action. However, decision theory is sometimes based on relatively restrictive premises so that its application to the climate or adaptation problem is limited (see Table 4).

Procedure	Description	Evaluation
CLEAR RECOMMENDATION FOR ACTION		
Decision Theories (including, among others, benefit-cost, cost-efficiency and multi-criteria analyses, as well as portfolio theory)	Formal quantitative procedures to determine the best choice from a range of alternatives. This requires the definition of the full quantity of decision alternatives, their respective results as well as their evaluation. Uncertainty is taken into account by assigning occurrence probabilities to the results.	Advantages: • Quantitative results • Reproducibility of the analysis • In principle, all dimensions of the climate problem can be included Disadvantages (restrictive assumptions): • Single decision maker with well-defined preferences • Finite set of decision alternatives • Results must be comparable and therefore must be displayable in a specific unit of measurement (e.g. € or utility). • Rationality • Uncertainty must be quantifiable
Game Theory	Delivers information about the implications of the decisions of multiple actors. In doing so, the expectation of each individual actor is taken into account in relation to the behaviour and expectations of the other actors (strategic interaction).	Clear recommendations for action can be derived. If the level of complexity is too high the analysis is restricted to a purely descriptive level, hence giving information about the outcomes of the actions in a specific context.
NO CLEAR RECOMMENDATION FOR ACTION		
Public Finance	Encompasses numerous approaches incl., among others, the theory of second best.	Allows the investigation of trade-offs between efficiency and other criteria.
Bayesian Networks	Probabilistic models with dual structure: 1.) Graph in which nodes represent (random) variables and angles represent conditional dependencies or probabilities between these variables. 2.) Quantification of the conditional probabilities between the variables.	Allow the analysis of complex decision systems (multiple goals, uncertainty, dynamics) taking learning processes into account.
Tolerable Windows and/or the Safe Landing Approach	Given defined, exogenous framework conditions that rule out non-tolerable climate change on the one hand and non-acceptable (adaptation or mitigation) measures on the other, the potential scope for action is identified on the basis of causal relationships between climate and society.	Advantages: • Well-founded narrowing down of the action alternatives. • Stimulates critical scrutiny of the set goals. Disadvantages: • No information regarding the selection of framework conditions. • The result of the procedure delivers no "best" alternative for action (or no "best" action pathway).

Prescriptive Rules of an ethical and cultural nature	Refers primarily to the implications of various forms of social organisation.	Advantage: • Allows an analysis of the interactions between the choice of political measures and the social structure. Disadvantages : • Limited application to the climate problem. • No quantitative analysis.
Focus groups, political role playing and simulations	Encompasses a range of research activities to support the decision-making process. In general, potential action outcomes are examined in the context of group work, whereby the individual group members take on different roles within the framework of a simulated decision environment. Computer-aided models can be used to support the investigations.	Results are mainly of a pedagogical nature and are not reproducible.

Table 4: Procedures for decision making when pursuing multiple goals (following IPCC, 2001a)

62. In decision theory, benefit-cost, cost-efficiency and multi-criteria analysis methods play an important role in decision support in the context of adaptation (KLEIN and TOL, 1997). **Benefit-cost analysis** makes it possible to consider multiple goals simultaneously by breaking them down to the same monetary scale so that possible synergies and conflicts between the goals can be balanced out (see Section 3.1 for more detail). Ultimately, the action alternative that demonstrates the greatest net benefit, i.e. the greatest difference between the benefit and the cost of the option, is the one to be selected. If the benefit and the costs (e.g. in the case of investment decisions) span over several periods, then they are to be related to the present value by discounting. In practice, however, massive uncertainties about the impacts of climate change and informational problems in the assessment of damages in relation to non-monetary goods (e.g. biodiversity loss) make it difficult to quantify the benefit side (KLEIN et al., 2005). **Cost-efficiency analysis**, which explicitly excludes the benefit side, offers a way out of this dilemma. It concentrates on selecting the measure which achieves the set targets at the lowest possible cost, thereby getting around the previously mentioned information problems.[11] Benefit-cost and cost-efficiency analyses do make it possible to consider multiple goals, but they evaluate the response options according to just one criterion – the optimality or cost-efficiency criterion. If additional criteria are to be considered in the selection (e.g. flexibility or acceptability) it is necessary to resort to **multi-criteria analysis** (HALLEGATTE, 2009). Here the qualitative and quantitative criteria are weighted according to specific considerations and the available measures are ranked accordingly (see KLEIN and TOL, 2007 for more details). MEYER et al. (2011a) develop a special **software-based multi-criteria method** into which, in particular, **data afflicted with uncertainty** in relation to the impacts of climate change can also be introduced. They apply this method on the basis of two case studies in which they evaluate structural (hydraulic engineering) and non-structural (e.g. warning systems or resettlements) flood protection measures using several criteria. An-

[11] Integrated Assessment Models represent a potential tool for implementing cost-efficiency analyses. They make it possible to calculate the adaptation-mitigation combination which guarantees the implementation of a given warming or emissions target at the lowest possible cost (see No. 42).

other example of its application can be found in MEYER et al. (2011b). Here various water management options for adapting to altered climatic conditions in the Elbe catchment area are assessed according to economic and ecological criteria.

63. **Portfolio theory** also belongs to decision theory, although its role in the adaptation problem is a rather minor one (IPCC, 2001a). It is essentially concerned with determining the optimal composition of certain investment portfolios which differ in terms of return and risk. The various "investment vehicles", or in this case rather "action alternatives" (elements of the portfolio), are represented by a probability distribution of the expected return. Only the variance and the expected value of the return enter into the decision maker's utility function. The efficient portfolio is distinguished on the basis that no other portfolio exists with a higher expected return and an equal/lower risk or a lower risk and an equal/higher expected return. However, for many adaptation decisions this analysis clearly falls short of the mark.

64. A major limitation of decision theory lies in the assumption that only a single decision maker influences the outcome of an action. In reality, however, outcomes are frequently dependent on the actions of multiple actors. Such strategic decision situations can be analysed using **game theory methods**. Here formal models are applied from which, in principle, clear recommendations for action can be derived. In highly complex decision situations, e.g. when actors are pursuing several goals at the one time, a descriptive analysis of the strategic interaction will have to do (IPCC, 2001a).

65. Furthermore, several procedures exist that make do from the start with such a descriptive analysis or the narrowing down of possible response options (IPCC, 2001a). **Public finance**, which comprises numerous individual approaches and theories, enables the investigation of trade-offs between optimality and other goals or criteria, such as e.g. equity. Building on this, so-called second best goals, i.e. compromise solutions between multiple competing goals, can be identified. CATENACCI and GUPPONI (2010) as well as MUSANGO and PETER (2007) advocate the use of Bayesian networks to support adaptation decisions. Bayesian networks are probability theory models with a dual structure: on the one hand they comprise graphs in which the nodes represent (random) variables and the angles represent conditional dependencies or probabilities between these variables. In the context of climate adaptation, complex decision systems consisting of different adaptation measures (possibly at different time points and with uncertain effects) as well as uncertain impacts of climate change and damage events can be illustrated in this way. On the other hand, these networks enable the quantification of conditional probabilities between variables, even when these are not directly connected (in other words, across several nodes). Moreover, learning processes can be reproduced by updating the conditional probabilities with the Bayesian method whenever new information becomes available. Consequently, Bayesian networks are predestined to model the characteristic framework conditions given in dynamic adaptation decisions (uncertainty, irreversibility, possibility of learning) and support decision-making. The **tolerable windows or safe landing approach** is primarily aimed at limiting the quantity of eligible policy options. Integrated Assessment Models based on defined objectives or framework conditions are normally used to determine which scope for manoeuvre is compatible with these objectives and which measures are to be ruled out. Thus, as an example, given a specific warming objective as well as a specific budget restriction, it can be estimated in which range and over what period the adaptation investment of a country should take place. However, due to its

high level of aggregation this procedure is not suitable for selecting certain measures. Finally, the **analysis of prescriptive rules of an ethical and cultural nature** as well as **political role playing and simulations** (e.g. in the context of so-called focus groups) are two sociological and political science approaches of note for conducting a qualitative analysis of the decision process. The first of these two approaches examines the importance of different forms of social organisations in relation to the implementability and effect of the adaptation measures. The simulations of adaptation policy decision processes deliver mainly pedagogical, non-reproducible results. Due to the laboratory-like character of the simulation these results are of relatively low relevance for real adaptation decisions (IPCC, 2001a).

4 Barriers to Autonomous Adaptation and the Legitimisation of Government Intervention

66. Adaptation to changing framework conditions is of course not a novel phenomenon, but rather an ongoing task for all societies and economic actors. From an economic theory perspective, markets always promise a superior capacity to deal with both uncertainty and changed circumstances. Hence, initially a certain preference for decentralised and autonomous adaptation to altered climate conditions exists. Against this background, from an economic standpoint, there is a definite need for a detailed explanation of where and how an adaptation to climate change will be organised by the government (cf. e.g. PETHIG, 2011). Basically the legitimacy of government interventions is given, insofar as the autonomous adaptation is subject to certain barriers and therefore does not meet the set goal(s) (see Chapter 3).[12] Most of the relevant literature deals with the topic of these barriers on a broad basis without systematically incorporating them into economic theory (Section 4.1). However, a second branch attempts to work out theory-based legitimisations (see Figure 6 for an overview). These are based, on the one hand, on the missing of the economic objective of optimality (Section 4.2). On the other hand, government interventions are motivated by the pursuit of goals unrelated to efficiency, since these are generally not transported by the market mechanism (Section 4.3).

[12] The topic of barriers to adaptation policy is to be distinguished here; it is dealt with in Section 5.2.

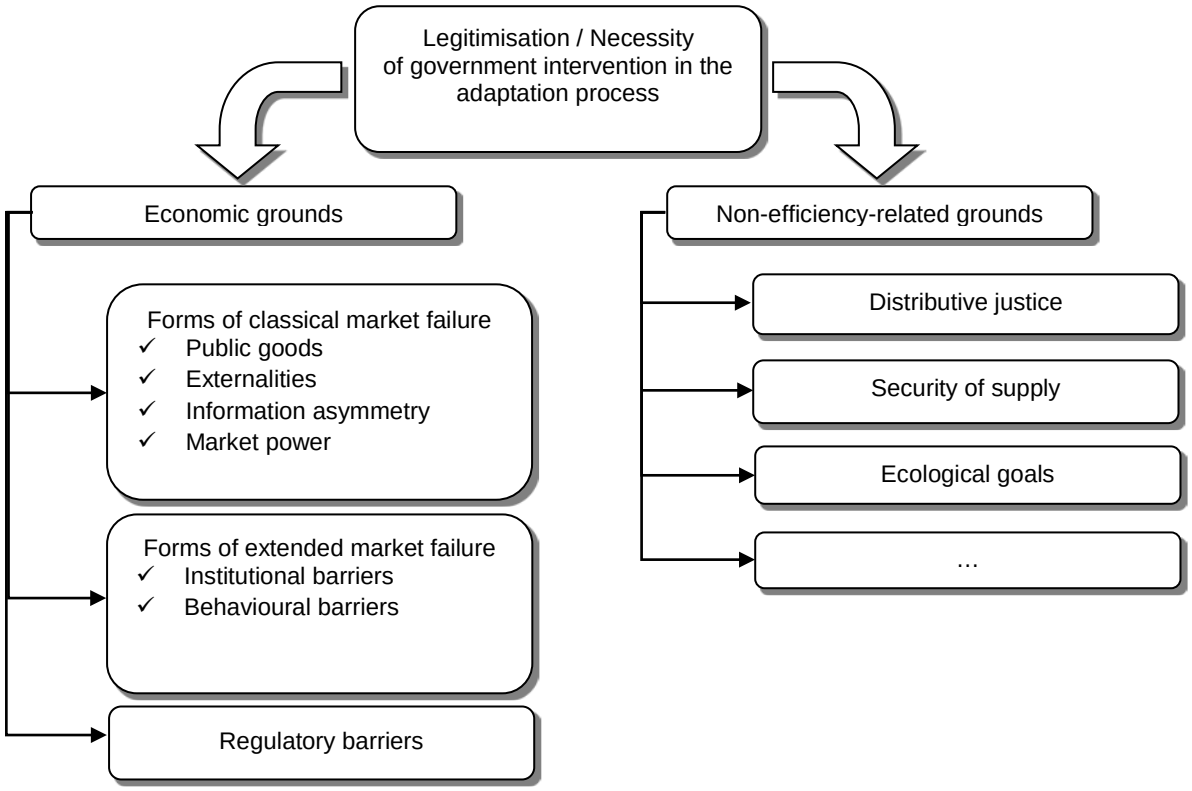

Figure 6: Legitimisation and Necessity of Government Intervention in the Adaptation Process (according to GAWEL and HEUSON, 2011)

4.1 Identifying fundamental barriers to autonomous adaptation

67. The following studies identify basic obstacles to autonomous adaptation as starting points for government interventions **without systematic reference to economic theory**. According to the Intergovernmental Panel on Climate Change fundamental barriers to adaptation include a lack of access to (economic) resources, lack of availability of technologies, insufficient information and skills or qualifications, insufficient or unfavourable infrastructural or institutional preconditions as well as (social) inequality (IPCC, 2001b). HULME et al. (2007) choose an **interdisciplinary approach** to reveal the barriers to adaptation which, in their view, can be traced back to political, social or psychological origins. Moreover, they differentiate between **barriers and limits** to adaptation, whereby the latter, in contrast to barriers, are not insurmountable. As typical barriers the authors refer to individual and social factors, such as e.g. inertia or a political culture of risk denial; as typical limits, the uncertainty surrounding the impacts of climate change as well as critical thresholds in ecological systems which, if exceeded, would give rise to irreversible damage. However, they point out that the differentiation between barriers and limits to adaptation cannot be generalised, rather it should be seen in the context of the values of a society and the goals being pursued with the adaptation. ADGER et al. (2009) take a similar approach, whereby they place a strong focus on **technological barriers**.

68. In addition to these works of a general nature, several studies exist which – mostly in the context of case studies – examine **adaptation barriers in particular regions or sectors**.

WREFORD et al. (2009) analyse barriers in the **agricultural sector**, while ANTLE (2009), HASSAN and NHEMACHENA (2008) and PAAVOLA (2004) concentrate on the USA, Africa and Tanzania. POPP et al. (2009) also devote themselves to the agricultural sector. They use a **coupled model** with **ecological** (vegetation dynamics) and **economic components** (optimisation of farmers) to examine the conditions of and barriers to successful adaptation in the area of farming. ALPIZAR et al. (2009) pursue the same objective, but for this they conduct a field experiment with coffee growers in Costa Rica. GTZ (2007) concentrates on barriers typically encountered in developing countries. KELLY and ADGER (1999) conduct a similar study specifically for Vietnam where they identify the lack of access to resources due to limited property rights as a fundamental barrier. BATTAGLANI et al. (2009) and COVICH (2009) focus their attention on the European **wine growing industry** and the **supply of drinking water,** respectively, while KREIBICH et al. (2005) study the barriers that arose in the context of the Elbe river flood of 2002.

4.2 Economic legitimisation of government intervention

69. According to CIMATO and MULLAN (2010) failure to achieve the objective of optimality can be traced back to **forms of classical market failure** (public goods, externalities, information asymmetries or market power, Section 4.2.1) or **forms of extended market failure** (institutional or behavioural obstacles, Section 4.2.2). On the other hand, **regulatory obstacles** must also be considered (Section 4.2.3).

4.2.1 Forms of classical market failure

70. From an economics perspective, as long as the market mechanism motivates optimal (No. 23) adaptation measures by private actors, government interventions in the adaptation process or government-implemented adaptation measures are neither necessary nor legitimate (cf. e.g. Mendelsohn, 2000, AAHEIM and AASEN, 2008). The opposite applies when the individual deviates from the social benefit-cost calculation or when **forms of classical market failure** – public goods, externalities, information asymmetry or market power – are present (cf. e.g. OECD, 2008, DANNENBERG et al., 2009, OSBERGHAUS et al., 2010a, BMF, 2010 or HALLEGATTE et al., 2011). In a simple microeconomic model (No. 26) MENDELSOHN (2000) provides **formal proof** that the different forms of market failure lead to inefficiencies in autonomous adaptation behaviour. BOSELLO et al. (2009) as well as DE BRUIN and DELLINK (2009) capture the effects of suboptimal autonomous adaptation on the **macroeconomic level** with the aid of Integrated Assessment Models (No. 43).

71. Many adaptation measures display the characteristics of public goods which, as is generally known, will lead to a suboptimally low level of private or autonomous adaptation (DANNENBERG et al., 2009, FANKHAUSER et al., 2009, BMF, 2010, OSBERGHAUS et al., 2010a). CIMTAO and MULLAN (2010) differentiate in the context of adaptation between **global** (e.g. the provision of information or basic research into drought-resistant crops), **national** (e.g. adaptation measures in the areas of infrastructure or healthcare) and **local public goods** (e.g.

dams for the protection of specific areas).[13] DOBES et al. (2010) highlight the key importance of **provision of information** by the government in order to guarantee greater **planning certainty** in the case of private investments into adaptation.

72. Furthermore adaptation measures can be accompanied by positive or negative **external effects** which need to be internalised through government interventions. For example, it is possible that interdependencies exist between several local adaptation measures such as, e.g. competition for a single water source used for different irrigation systems, which must be coordinated by the government (DANNENBERG et al., 2009). In addition, adaptation measures can cause negative environmental externalities such as, e.g. increased CO_2 emissions due to the use of air-conditioning systems, which in this case would imply a suboptimally high level of adaptation (TOL 2005). Within the framework of a microeconomic model, EISENACK (2009) considers a particular constellation that causes a positive external effect. A price-taking firm can reduce the adverse effects of extreme weather events on its production by means of adaptation measures. In its calculation, the firm neglects the positive effect of its adaptation effort on the consumer surplus – production costs fall as a result of the adaptation causing a higher equilibrium quantity and a likewise a lower price. Consequently, from a social perspective, the company's adaptation performance is too low.

73. The **asymmetric distribution of climate- or adaptation-relevant information** leads – for instance in the real estate or insurance markets – to the well-known problem of adverse selection or moral hazard thus requiring government relief (cf. e.g. DANNENBERG et al., 2009, SCHWARZE, 2008 or SCHWARZE and WAGNER, 2007).

74. **Market power** can occur in two ways in the case of adaptation measures: First of all, in the adaptation of infrastructural goods (or in their creation for adaptation purposes) such as rail or power networks where efficient production implies a natural monopoly (FANKHAUSER et al., 2009). EISENACK (2010) takes on another market power-related problem that is unique in the literature: in a microeconomic model he provides proof that **Cournot oligopolists** achieve suboptimal adaptation performance **in an endogenous market structure**.

4.2.2 Forms of extended market failure

75. Optimal market outcomes are linked to certain **institutional conditions and frameworks** (DANNENBERG et al., 2009, BMF, 2010). A **functioning system of property rights** is of key importance. Without such a system long-term investments, which play a decisive role in the adaptation process, would not be forthcoming and the success of both government and private adaptation actions would be endangered (OSBERGHAUS et al., 2010a). For instance, the implementation of an agricultural irrigation system can only take place when the property rights to the water sources in question are clearly defined. Moreover, the judicial system is indispensable as a public service to ensure the enforceability of those rights. Institutions that guarantee the financing of individuals or companies with insufficient budgets, i.e. an appropriate banking and credit system (e.g. micro-credits), also play an important role in enabling the implementation of necessary adaptation measures (CIMATO and MULLAN, 2010).

[13] Club goods are also frequently mentioned in connection with local public goods that permit exclusion (BMF, 2010).

In relation to **institutional conditions**, inertia and/or **path dependencies** that stand in the way of the timely modification or creation of adaptation-relevant institutions also prove problematic. Taking the US water sector as an example, LIBECAP (2011) demonstrates the reasons for these path dependencies. The relevant institutions, e.g. ordinances, were created at a time when water was used primarily for agricultural purposes and are therefore no longer adequate in the current context of mainly industrial water use. However, a corresponding modification of the institutions is sometimes associated with significant costs and is therefore not always possible. Consequently, the existing institutional framework conditions make it difficult to implement the required adaptation measures in the water sector.

76. Inhibitory framework conditions can also manifest as **technological path dependencies**. These stem from the fact that many vulnerable system components, such as real estate or energy networks, are based on long-term investments. These investments become sunk costs ex post, resulting in corresponding rigidities and thus, ultimately, in suboptimal adaptation because the necessary shifting or substitution of these components cannot be carried out when required (AAHEIM and AASEN, 2008).

77. The reasons for suboptimal adaptation behaviour may also lie with the adapting actors who, contrary to neoclassical economic theory, do not act with perfect rationality and perfect foresight. In view of the enormous complexity of the climate change/adaptation problem it is likely that decisions related to adaptation are subject to **limited rational behaviour**. Such behaviour may, alternatively, be evoked by cultural aspects, such as certain moral concepts or traditions (IPCC, 2007b). Furthermore, human behaviour is often characterised by temporal inconsistencies and the well-known behavioural economics phenomenon of **hyperbolic discounting**, which can lead to behaviour such as **inertia**, **procrastination** or **strategic ignorance** (CIMATO and MULLAN, 2010 as well as CARILLO and MARIOTTI, 2000). This inertia or hesitation is largely due to the fact that the benefits of the adaptation measures, in contrast to the costs, often accrue well beyond the planning horizon of the respective actor because of the time-lag in the impacts of climate change.

78. GROTHMANN et al. (2009a) identify important **psychological or behavioural economic determinants** of individuals' **adaptation behaviour** that may be responsible for insufficient incentives for autonomous adaptation – cf. Figure 7. In doing so, a distinction is made between determinants which emerge from the general action context and those which affect both the motivation and the execution of the action. On the other hand, with regard to motivation, a differentiation is made between problem-related (e.g. perception of the problem or environmental awareness) and action-related factors (e.g. convictions about effectiveness or subjective norms), while with regard to the execution of the action, customs/habits and other factors (e.g. clarity of the target or emotions) are decisive to adaptation behaviour. In view of these diverse influences it becomes clear that the mere provision of information by the government does not necessarily guarantee efficient autonomous adaptation. OSBERGHAUS et al. (2010b) come to the same conclusion. Within the framework of a behavioural economic or **risk psychology approach** they use econometric methods to demonstrate that certain psychological aspects and risk perceptions can have an inhibitory effect on information processing. GIFFORD (2011) identifies various psychological factors (e.g. insufficient problem recognition, ideological world views which exclude environmentally friendly behaviour, ad-

herence to customs/habits or lack of trust in experts) that could explain the inertia of actors in the area of adaptation.

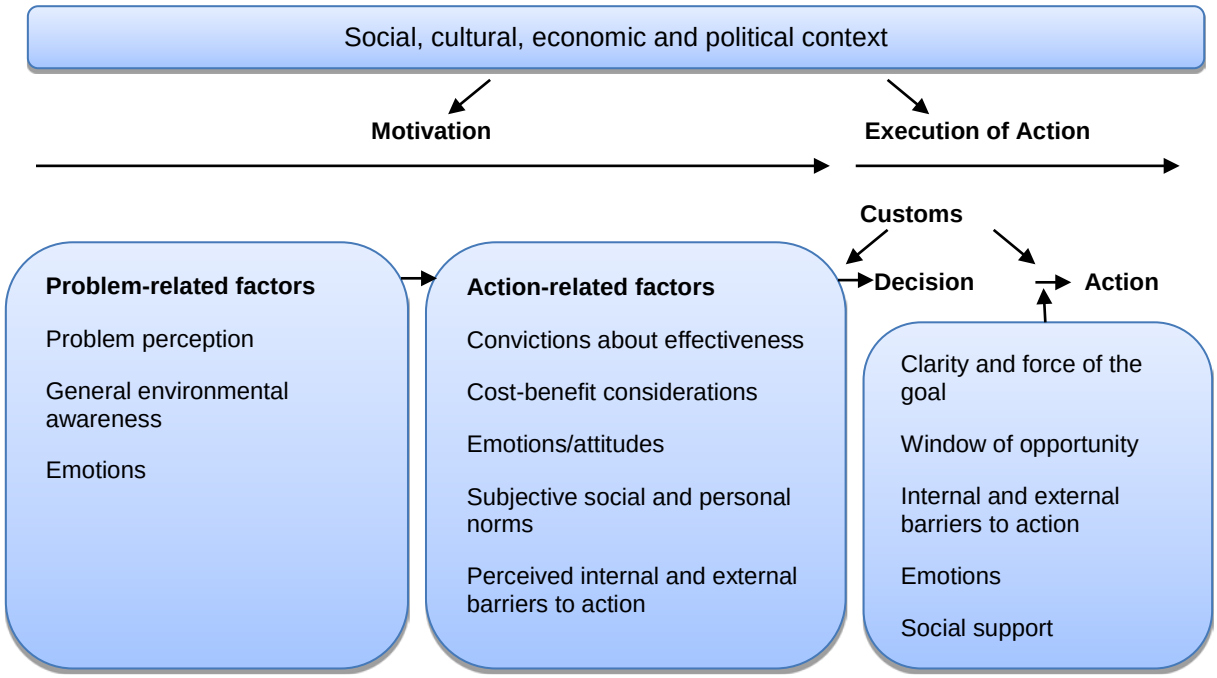

Figure 7: Determinants influencing climate protection and climate change adaptation actions (GROTHMANN et al., 2009)

4.2.3 Regulatory barriers

79. Barriers to autonomous adaptation are not only rooted in the framework conditions and characteristics of the market. Existing **regulatory and political interventions**, even when aimed at other, non-adaptation-related goals (e.g. intervention in the areas of biodiversity, water or agriculture), can **significantly influence decisions on autonomous adaptation** (CIMATO and MULLAN, 2010). For example, agricultural policy measures are reflected in the resilience of natural systems used for agricultural production.

80. KESKITALO (2009) argues that in view of increasing globalisation individual regional or national regulatory interventions are not the only ones that need to be considered in the context of autonomous adaptation decisions – sometimes whole sets of measures, right through to **governance networks**, influence the decision situation at different levels. On the basis of a case study in the area of forestry, reindeer husbandry and fishing in Scandinavia the author examines how, in view of this growing complexity, local stakeholders perceive vulnerability and adaptive capacity in their sphere of action and how they make adaptation-related decisions.

81. FANKHAUSER et al. (1999) stress that virtually all policy areas (health, education, the economy, the environment etc.) make a significant contribution to shaping the framework conditions for autonomous adaptation. Hence it is essential to consider adaptation-relevant

aspects in all pertinent decisions and interventions so that regulatory barriers can be prevented from the outset. In the literature this aspect is often summarised under the concept of "**mainstreaming**". Using case studies, OECD (2009) demonstrates how adaptation can be integrated into development policy. KLEIN et al. (2005) deal with this question on the conceptual level and identify the regional development policy area as particularly relevant in relation to incorporating adaptation aspects.

4.3 Pursuing non-efficiency-related goals

82. In addition to the economic legitimisation of government adaptation measures on the grounds of market failure, **government intervention** is also necessary to **implement** the non-efficiency-related goals described in Section 3.2, especially since these are not conveyed through the market mechanism (DANNENBERG et al., 2009, OSBERGHAUS et al., 2010a). Several studies highlight from their point of view the most important goals and aspects, such as social insurance against catastrophic events (FANKHAUSER et al., 2009), overcoming poverty (HALLEGATTE et al., 2011) or equity and justice (PAAVOLA and ADGER, 2002).

5 Governance and Instrument Choice

83. Essentially, three strands of literature on the topic of governance and instrument choice can be identified. In the first of these, **descriptive analysis** is used to record and categorise potential and already implemented adaptation instruments, institutions and governance structures (Section 5.1). The second strand approaches the topic on a **positive level** by examining the barriers to (optimal) government intervention (Section 5.2), while the third strand delivers recommendations for the configuration and choice of instruments and for the design of institutions and governance structures on a **normative level** (Section 5.3).

5.1 Descriptive analysis: Governance structures, institutions and instruments

84. The literature aimed at drawing up an inventory of possible and existing adaptation instruments, institutions and governance structures is divided into two sections: The first provides various general, **fundamental categorisations** and systematisations (Section 5.1.1). The second comprises numerous analyses aimed at **individual sectors** or **regions** (Section 5.1.2).

5.1.1 Fundamental systematisation

85. A systematisation of government adaptation instruments can, in principle, be done using the categorisation of general adaptive measures presented in Table 2 (No. 13). However, in the literature various systematisations have been developed which account for the specific characteristics of government interventions or instruments. These do not contradict the criteria in Table 2, but should rather be understood as complementing or clarifying them. OECD

(2008) systematises the possibilities for government intervention in the area of adaptation according to the **purpose** or **intention** of the intervention:

- sharing of losses (e.g. reconstruction through public funds),
- modification of the threat (e.g. flood protection),
- avoidance of climate change impacts by means of
    - structural/technological measures
    - judicial or regulatory instruments
    - institutional or administrative measures
    - market-based instruments
    - on-site measures,
- use changes (e.g. conversion of agricultural area into wetlands for coastal protection),
- change of location (e.g. relocation of crop growing),
- extraction of information (e.g. through research),
- control of behaviour through education, information and regulation.

86. In contrast, the systematisations of CIMATO and MULLAN (2010) and – deviating only slightly from these – HALLEGATTE et al. (2011) are based on the **type of government intervention**:

- direct regulation (e.g. technology or process-related restrictions or prohibitions),
- market-based (economic) instruments (e.g. taxes or tradable usage rights),
- research and monitoring programmes,
- provision of information,
- investment in infrastructure (e.g. dyke construction),
- reallocation measures (e.g. compensation or credit programmes),
- institutional reforms (e.g. in the water or agricultural sector).

87. The Scientific Advisory Board to the German Federal Ministry of Finance systematises adaptation instruments according to the different **forms of market failure** at which they are aimed (BMF, 2010). GOKLANY (2007) concentrates on institutions and measures which are targeted specifically at building **adaptive capacity** and which at the same time comply with sustainable development goals. Lastly, the Intergovernmental Panel on Climate Change (IPCC, 2007a) and AAHEIM and AASEN (2008) choose the **impacts of climate change and the sectors affected by climate change**, respectively, as their categorisation criterion.

88. GROTHMANN et al. (2009a) introduce three main starting points specifically targeted at **overcoming psychological barriers to adaptation** (for a detailed description of the individual instruments see GROTHMANN et al., 2009b). The first set of instruments is aimed at the actors who are to be motivated to change their behaviour. These instruments essentially address the knowledge (e.g. personal or non-personal transfer of knowledge), norm perceptions (e.g. voluntary commitment or social models) or the emotions (e.g. experience-based techniques) of those actors. The second set of instruments aims to influence the behavioural environment of the actors, e.g. via organisational changes or by further educating key actors. Finally, attempts are made to systematically exploit existing social networks and interpersonal relationships in order to promote the autonomous spread of adaptive activities, e.g. by exerting the appropriate influence on multipliers such as teachers or club presidents.

5.1.2 Sector- and region-specific studies

89. **Sector-specific analyses** cover the areas of health (FÜSSEL and KLEIN, 2004), the insurance industry (BERZ, 2005 and HERWEIJER et al., 2009), public infrastructure (NEUMANN and PRICE, 2009), agriculture (WREFORD et al., 2009), civil protection (FOA, 2009), terrestrial ecosystems (RUNNING and MILLS, 2009) and – in a way as a cross-sector – urban areas (HUNT and WATKISS, 2011).

90. Some studies record cross-sectoral government adaptation measures or governance structures for individual **countries or regions**: e.g. Germany (DANNENBERG et al., 2009, OSBERGHAUS et al. 2010a, GAWEL and HEUSON, 2011 conduct a critical evaluation of the "Adaptation Action Plan", linked to the German adaptation strategy), the Netherlands (DE BRUIN et al., 2009), Vietnam (KELLY and ADGER, 1999 and DANG et al., 2003) and Papua New Guinea (MERCER, 2010). GAGNON-LEBRUN and AGRAWALA (2006) pool the implemented measures of the **industrial countries**, while HARDEE and MUTUNGA (2010) as well as the WORLD BANK (2010b) pool those of the **developing countries**. In connection with the latter, a particular focus is placed on **financial aid** instruments and approaches: PRZYLSKI and HALLEGATTE (2010), AYERS and HUQ (2008), HOFF et al. (2005), STEWART et al. (2009), UNFCCC (2007) and UNFCCC (2008). Furthermore, with a study of the European coastline, **specific regions** are also examined (PRC, 2009).

91. In another group of studies the degree of specialisation is increased by combining **sector-** (No. 89) and **region-specific analyses** (No. 90): Norwegian cities (AMUNDSEN et al., 2010), US agriculture (ANTLE, 2009), US drinking water management (COVICH, 2009), the European wine-growing industry (BATTAGLANI et al., 2009), flood protection in China (LAU, 2006), the agricultural sector in Tanzania (PAAVOLA, 2004), the agricultural sector in Austria (PRETTENTHALER, 2006), agricultural water systems in South America (SEO, 2011), and the water resources of the Alps (EEA, 2009).

5.2 Positive analysis: Barriers to public adaptation

92. Barriers to public adaptation represent the counterpart of barriers to private adaptation (cf. Chapter 4) and are correspondingly determinants of policy failure i.e. suboptimal government adaptation measures that fail to achieve the set objectives mentioned in Chapter 3 or suboptimal design of the relevant instruments or institutions. In addition to these individual general deliberations on barriers to public adaptation (Section 5.2.1) there are numerous studies that deal with barriers that arise in certain specific countries, regions or sectors (Section 5.2.2).

5.2.1 General barriers

93 Taking an interdisciplinary approach that features psychological, political and socio-economic components, ADGER et al. (2009) argue that barriers to public adaptation often lie in the **culture, value systems** and **traditions** of a society. These not only determine the acceptance or reservations of the general population and various stakeholders towards government-implemented adaptation measures and instruments, they also influence goal setting and the capacities of the relevant decision makers, and may even be detrimental to optimal adaptation policy. The Intergovernmental Panel on Climate Change identifies poorly functioning **financial markets**, weak or instable **institutional** and **legal framework conditions**, socially or culturally induced **rigidities** as well as **knowledge or qualifications deficits** on the side of government decision makers and authorities as significant barriers (IPCC, 2001b). YOHE (2001) also points to the **human and social capital** of a society, the **management capacities** of the decision makers as well as **public perception** of the adaptation policy as essential determinants of the implementability and enforceability of government adaptation interventions.

94. MICHAELOWA (2001) chooses a somewhat different approach. He argues from the **Public Choice** perspective that **self-benefit maximising interest groups and actors** influence the political adaptation process and can distort relevant decisions. Such groups include emitting industries, the climate protection industry as well as the adaptation industry, government-independent groups such as environmental protection associations, the media, bureaucrats and voters. And lastly, of course, the self-interested behaviour or pursuit of power of the decision makers themselves can lead to suboptimal adaptation interventions. Although Public Choice is without a doubt a promising theory for the analysis of barriers to public adaptation, so far there are hardly any studies that pursue this approach. MOSER and EKSTROM (2010) develop a governance-based, **conceptual framework for identifying barriers** in the different phases of the adaptation process, which in particular sheds light on the respective demands on the actors involved and their relationships.

5.2.2 Analysis of sectoral and regional barriers

95. The sector- and region-focussed literature is based mostly on field studies. Here the attention is directed above all to the barriers to public adaptation typically present in **developing and emerging economies** (BARR et al., 2010, DELLINK et al., 2009, as well as HARDEE and MUTUNGA, 2010). Within this thematic area various **specific problems** are examined. KELLY and ADGER (1999) deal with early warning systems for tropical storms in the coastal regions of Vietnam, DULAL et al. (2009) with Small Island Developing States (SIDS), KOCH et al. (2007) with adaptation-relevant institutions and governance structures in South America, SEO (2011) with agricultural irrigation in South America, and LAU (2006) with civil protection and flood protection in Chinese coastal regions. These studies essentially hold the same barriers responsible for the adaptation policy problems of developing and emerging economies:

- insufficient financial power,
- insufficient institutional capacity,

- governance problems (e.g. lack of coordination and conflicts between the different authorities and ministries),
- cultural barriers (e.g. reservations about the use of foreign technologies).

96. Furthermore, the – mostly sector-specific – barriers of **industrial countries** are analysed. On the basis of a survey of **Norwegian towns and communities**, AMUNDSEN et al. (2010) show that the barriers are manifested, first and foremost, in a lack of institutional capacities and in the insufficient coordination and cooperation between national and local government bodies. In a case study of Sydney's boroughs, MEASHAM et al. (2011) come to similar conclusions. Moreover, they see the barriers to adaptation as being rooted primarily in insufficient political leadership ability and competing political intentions. A lack of coordination between authorities and states, as well as rigid procedural rules, complicate adaptation in the area of **water resources management in the Alps** (EEA, 2009). COVICH et al. (2009) consider conflicts between local and regional stakeholders as essential barriers in **US drinking water management**. CRABBÉ and ROBIN (2006) examine specific institutional barriers in the area of adaptation of water infrastructure in Eastern Ontario. NEUMANN and PRICE (2009) deal with the barriers in the area of public infrastructure, which they see as being rooted in insufficient integration of planning between the different sectors and areas. KOPYTKO and PERKINS (2011) state that the technological lock-in in the **atomic energy** and the massive commitment of resources associated with it significantly compromise the adaptive capacity of the state.

97. **Removed from the specific context of industrial or developing countries**, ALBERINI et al. (2005) address the **health sector**, for which they develop an adaptive capacity index on the basis of an expert survey and econometric methods. At the same time this index provides information about barriers to adaptation that are above all to be found in the structure of the healthcare system. FOA (2009) also applies econometric methods in a comparative study of country-specific barriers to adaptation in the area of **civil protection**. The results show that above all weak, dependent civil societies and a lack of rights of co-determination or participation for women are detrimental to optimal public adaptation. AYERS and HUQ (2008) reveal barriers in relation to **UNFCCC-**organised **adaptation aid**, which include financial restrictions, unclear allocation criteria and high transaction costs, among others.

5.3 Normative analysis: The design of adaptation policy and instrument choice

98. On the basis of the instruments and design options for adaptation policy described in Section 5.1, the literature provides various **policy recommendations** on the normative level, which are expected to help overcome barriers to public adaptation (Section 5.2) and achieve the goals set (Chapter 3). In this context, BALBI and GUIPPONI (2009), as well as PATT and SIEBENHÜNER (2005), discuss the potential of **Agent Based Models** to realistically reflect the process or system of adaptation policy, taking the said barriers into account, so that appropriate recommendations for political action can be derived. On the one hand they target **concrete instruments and measures** (Section 5.3.1). However, more holistic recommendations that address the **governance of adaptation** as a whole, i.e. all the relevant institutions, instruments and regulations in a specific field of action (Section 5.3.2), are clearly in the majority. It has to be stated that most of the relevant studies **argue qualitatively**, and although the

link to economic theory is sought, this is done **without the use of models or econometric evaluations**.

5.3.1 Instruments and measures

99. Normative analyses of government adaptation instruments and measures are mainly **context-dependent** or **problem-focussed** and are also limited primarily to the choice, but not to the design of said instruments and measures. An exception here is GROTHMANN et al. (2009a), who make general recommendations on the application of instruments which they suggest can be used to overcome psychological barriers to adaptation (No. 88). These instruments should, if possible, be applied in combination so that several psychological influencing factors can be addressed at once. Furthermore, target groups should be approached in phases when they are particularly open to change in order to guarantee the greatest possible effectiveness of the instruments. BARR et al. (2010) and DELLINK et al. (2009), on the other hand, derive recommendations for the design of **international adaptation funding** for developing countries by means of an index-based operationalisation of the equity goal. AGRAWALA and CARRARO (2010) also deal with the topic of financial aid. They make the case for the instrument of **micro-credits**, in particular, to fund short-term adaptation measures with a low volume of investment. Macro-financing instruments, on the other hand, should be used to fund long-term, resource-intensive measures. In the context of **developing countries,** various government **adaptation measures for the agricultural sector** are proposed and prioritised, whereby investment in education and research and the provision of information take priority (POPP et al., 2009, HASSAN and NHEMACHENA, 2008 as well as PAAVOLA, 2004).

100. Other studies place their focus on **industrial countries**. DANNENBERG et al. (2009) and OSBERGHAUS et al. (2010a) identify actual or potential inefficiencies of private adaptation in **Germany's** most important **economic sectors** and, on this basis, formulate sector-specific policy measures for implementation. COVICH (2009) drafts proposals for **US drinking water management**, while CIMATO and MULLAN (2010) do the same for the areas of **insurance, real estate, public infrastructure** and **ecosystems**, thereby explicitly taking potential barriers to public adaptation into account.

5.3.2 Governance

101. On the grounds of efficiency-related (Section 3.1) or other goals (Section 3.2), a number of studies give **general recommendations** for the design of adaptation governance. ADGER et al. (2009) call for adaptation policy to be oriented along an **ethical model** which respects and considers primarily those affected or threatened by the adverse effects of climate change and their the cultural background. BRUNNER et al. (2009) also favour an ethical model-based approach, whereby they attach special importance to the integration of science, politics and the people affected. Furthermore, the **leitmotif of integration** is likewise demanded in several other areas. For instance, ADGER et al. (2001), call for the integration of **adaptation and mitigation policy**, DANG et al. (2003) additionally call for the integration of development policy. The **active involvement of stakeholders** and those affected is seen to

play an important role (DULAL et al., 2009, HULME et al., 2007). DOBES (2010) and DULAL et al. (2009) advocate an integrated view of climate change-related and other **aspects of equity** in the political process. Increasing importance is being attached to the concept of **mainstreaming**, which envisages the integration of adaptation into all political and regulatory areas (beyond climate policy in the proper sense) (cf. z. B. CIMATO and MULLAN, 2010 and KLEIN et al., 2009). The same applies to the concept of **multi-level governance**, which stands for close cooperation, integration and coordination between decision makers and authorities on the different government hierarchy levels (cf. e.g. KESKITALO, 2010). In this context, a **decentralised implementation** of adaptation measures is recommended, which ideally begins where the concern and the know-how are greatest. If there are interdependencies between several measures a higher-level authority must take over the coordination (BMF, 2010 and HULME et al., 2007). Finally, a further key requirement lies in building **institutional capacity** in the area of adaptation (ADGER et al., 2001, CIMATO and MULLAN, 2010 and KLEIN et al., 2009).

102. In addition to these general policy recommendations several studies exist which focus alternatively on **specific problems, sectors or regions**. Many of these concentrate on adaptation governance in **developing countries** (HARDEE and MUTUNGA, 2010, KOCH et al., 2007, WORLD BANK, 2010b and VIGNOLA et al. 2009), whereby there is broad agreement on the key suggestions for decision makers: multi-level governance, less hierarchy, integration of stakeholders and local communities, integration of family and health policy as well as the sciences. With regard to **cross-border adaptation problems**, the studies recommend a clear definition of responsibilities and international cooperation (PRC, 2009 – EU Coastal Protection), as well as the coordination and integration of national legal systems, knowledge transfer and cooperation in the area of funding (EEA, 2009 – The Alps Facing the Challenge of Changing Water Resouces, CHRISCHILLES, 2011 – Research Cooperation with Developing Countries). In relation to **public infrastructure** NEUMANN and PRICE (2009) encourage the integration of area-specific planning. AMUNDSEN et al. (2009), on the other hand, identify multi-level governance as well as the building of local institutional capacity as playing a key role in adaptation policy of **Norwegian municipalities**. PAHL-WOSTL (2007) highlights the importance of the flexibility and learning ability of the relevant governance structures in the context of **flood management**. In relation to **adaptation funding**, PRZYLSKI and HALLEGATTE (2010) recommend that the focus be placed first on building institutional capacity and only in the second stage on concrete measures. AYERS and HUQ (2008) call for the integration of financial aid instruments in the areas of development and adaptation. Finally, MERCER (2010) sees synergies in the integration of adaptation policy and measures to reduce disaster risk.

6 The Role of Adaptation in International Agreements on Greenhouse Gas Reduction

103. The literature introduced in this section occupies a special position because climate adaptation is not its central research topic, but rather merely of indirect interest, within the framework of a positive analysis, in terms of its **impact on the outcome and stability of international agreements on greenhouse gas reduction**. Most of these studies are based on game theory models. Although the Scientific Advisory Board at the German Federal Ministry of Finance selects an argumentative approach, it does draw on findings from game the-

ory (BMF, 2010): The starting point of the argument is formed by the observation that the burden sharing between countries resulting from international agreement is determined largely by their **threat points**, i.e. their net benefits or payoffs in a non-cooperative equilibrium. By means of adaptation a country can reduce its residual damage (or increase the benefit from possible advantages of climate) and thereby improve its threat point. Consequently, that country must contribute less to the global public good of greenhouse gas reduction.

104. SCHWARZE et al. (2012) design a **general game-theoretical analysis framework (a detailed description is given in the annex)**, which takes up on the insurance-theoretical approach of EHRLICH and BECKER (1972) (No. 38): Two countries can confront climate change through mitigation or adaptation. The mitigation effort of a country reduces the global probability of occurrence of climate change-induced damages (self-protection) and thus represents a public good. In contrast, the adaptation effort of a country reduces only its own residual damages (self-insurance) and thus resembles a private good. The comparison of the adaptation-mitigation allocations in a cooperative and a non-cooperative equilibrium leads to the well-known result that the latter is suboptimal from a global perspective – here the countries do not consider that their own mitigation effort is positively reflected in the welfare of the other country. Moreover, the analysis of the non-cooperative setting shows that under certain circumstances the availability of the adaptation option can suspend the usual free-rider behaviour of both countries with respect to mitigation and sometimes even throw it into reverse – i.e. the mitigation efforts of the countries are then not strategic substitutes, but are strategically neutral or complementary. The general nature of this model approach allows for various expansions and refinements, as far as the institutional framework conditions or the actors and stakeholders involved in a specific problem are concerned.

105. In a static model with two risk-averse countries AUERSWALD et al. (2011) deliver the **formal proof** for the statements of the Scientific Advisory Board at the German Federal Ministry of Finance (BMF, 2010, No. 103). Furthermore, taking the adaptation option into consideration, they examine the **crowding-out problem** of global emissions mitigation, which stems from the concept that the unilateral emissions reduction of a single country may cause total global emissions to remain constant or even increase. The corresponding results are of a technical nature and hence will not be presented in detail here. It is interesting to note that of all the models described in this section, AUERSWALD et al. (2011) is, along with Schwarze et al. (2012), the only one to choose a stochastic approach. In their model approach EISENACK and KÄHLER (2012) demonstrate that **unilateral mitigation efforts may reverse the crowding-out effect**, i.e. they can increase the mitigation service of the other countries. The prerequisites for this are – in addition to the availability of the adaptation option – certain cost characteristics of the countries that react to the unilateral mitigation effort of the "Stackelberg leader".

106. Various studies focus on the **impact of adaptation on the stability** of international **climate protection agreements,** leaving out possible uncertainties. MARROUCH and CHAUDURI (2011) analyse this problem within the framework of a game with simultaneous decision making and multiple countries, each of which can elect to accede to the agreement. The game differentiates **several adaptation types** according to their impact on marginal damage. With increasing adaptation effectiveness the **stability of the climate agreement** grows, thus enabling a greater reduction in global emissions. In a similar model framework

BENCHEKROUN et al. (2011) delve deeper into the question of how different levels of adaptation effectiveness impact on stability and free-rider incentives. DE BRUIN et al. (2011) select a three-stage model to explore the question of stability. In the first stage the countries invest in proactive adaptation, in the second stage they have the option to accede to the climate change agreement, whereafter in stage three the mitigation service is performed.

107. BUOB and STEPHAN (2011a) consider a model with **two periods** and **several identical regions**, each of which has only a limited budget for adaptation and mitigation measures. They show that each region's willingness to cooperate with regard to emissions reduction is contingent on its original environmental quality and budget. Based on similar assumptions ZEHAIE (2009) investigates the question of whether adaptation is associated with strategic effects when it precedes or follows mitigation or when adaptation and mitigation occur simultaneously. The analysis is performed for the cases **full cooperation** (adaptation and mitigation), **partial cooperation** (mitigation only) and **no cooperation**. EBERT and WELSCH (2011) continue on this track of analysis in a two-stage game, however without explicitly modelling the budget restriction, whereby adaptation precedes mitigation. Their special interest lies in the question of how the productivity, pollution sensitivity and adaptive capacity of a country affects the mix of adaptation and mitigation in a cooperative and a non-cooperative equilibrium. Within the framework of a game theoretical model with multiple countries BARRET (2008) studies the relevance of the adaptation option for the willingness to cooperate. The model is characterised by the special feature that both adaptation (e.g. dam construction) and mitigation (e.g. construction of wind turbines) measures give rise to **fixed costs**, such that the **adaptation option promotes countries' willingness to participate**: Due to its fixed costs mitigation is only worthwhile for a country as long as a sufficiently large number of other countries contribute to it. The adaptation option diminishes the marginal return of mitigation and thereby increases the said required minimum number of countries.

108. A further group of models deals with the **role of adaptation funds** within international climate protection agreements, which are being promoted in the current discourse on climate policy as a financial aid instrument for developing countries by industrial countries. BUOB and STEPHAN (2011b) examine in a three-stage non-cooperative game (Stage 1: industrial country commits to mitigation effort; Stage 2: industrialised country performs adaptation and pays into fund; Stage 3: developing country performs adaptation and mitigation effort) the **incentives for industrial countries to pay into such funds** and discuss possible conclusions with regard to the realisation of climate protection agreements. Another approach targets the fact that adaptation funding influences the **fairness perception** of developing countries, while in turn this perception is crucial to their willingness to participate in international climate change agreements (PITTEL and RÜBBELKE, 2011). EISENACK (2011) analyses the **adaptation funding mechanism currently implemented in the Kyoto protocol**, which obligates industrial countries to pay a tax on emission rights acquired within the framework of the Clean Development Mechanism (CDM). This study is based on a partial equilibrium model of the CDM market in which, among other things, the net transfer payment-maximising tax rate is derived and the relationships between the emissions reduction target, tax revenue and excess burden are examined. A numeric specification of the model based on empirically estimated marginal mitigation cost curves for 13 world regions shows that sufficient funding on the basis of the current mechanism requires a much more ambitions emissions reduction target than that agreed within the Copenhagen Negotiations.

109. Finally HASSON et al. (2010) approach the same topic by applying **experimental economics** methods: In concrete terms, they examine the willingness to cooperate in a one-shot public goods game with very specific framework conditions; among other things, they assume that climate change leads with a certain probability to complete annihilation and consider only either-or decisions between mitigation and adaptation.

7 Guidelines to Support Decision-Making

110. A further branch of the literature assumes the task of providing political decision makers with economically sound orientation aids or guidelines for the **planning, ranking, implementation, evaluation and monitoring** of adaptation measures and instruments. However some warn against the use of these guidelines, since they are often too generalised and therefore do not take sufficient account of the specific context of each respective adaptation problem (PRC, 2009). Most of the guidelines are **holistically oriented**, i.e. they cover all steps from recording and evaluating the impacts of climate change right through to the selection and implementation of concrete policy measures. FÜSSEL (2008) provides an overview of selected holistic guidelines and evaluates these on the basis of various criteria (see Table 5).[14] BURTON et al. (2002) criticise the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC, 1994, see again Table 5) for over-focussing on the impacts of climate change (rather than on the vulnerability of the affected systems) as well as the insufficient consideration of uncertainty, and they attempt, with the design of their own guidelines, to overcome these shortcomings.

[14] The guidelines evaluated here address general adaptation policy, with the exception of WHO (2003), which is targeted at adaptation in the health sector. Strictly speaking, the evaluation is performed according to the usability of the guidelines for adaptation in the health sector. However most of the derived conclusions are of a general nature.

	IPCC (1994)	USCSP (1996)	UNEP (1998)	UKCIP (2003)	UNDP (2005)	WHO (2003)
Clear procedural structure	+	+	0	+	+	0
Flexible assessment procedure	0	0	0	+	+	0
Prioritisation of research efforts	0	0	0	+	0	0
Identification of key information needs	-	-	-	+	0	0
Integration of key stakeholders	-	0	0	0	+	+
Choice of relevant spatial and temporal scales	-	0	0	+	+	0
Balanced consideration of current and future risks	-	0	0	0	+	+
Management of uncertainties	0	0	0	+	+	0
Policy guidance in the absence of quantitative risk estimates	-	-	0	+	+	0
Prioritisation of adaptation actions	-	0	0	+	+	-
Mainstreaming of adaptation	-	0	0	+	+	+
Cross-sectoral integration	0	0	+	-	-	+
Assessment of key barriers to adaptation	-	-	-	-	0	0

Table 5: Evaluation of holistic adaptation guidelines (Füssel, 2008)
(degree to which criterion is met:+: well; 0: partially; -: not met)

111. In addition to these mostly general guidelines, there are some which are designed in a similarly holistic way but refer to a **specific context** or a **specific field of action**. On the basis of a general theoretical framework GAMBARELLI and GORIA (2010) develop a guideline for Italian adaptation policy. KLEIN et al. (1999) focus specifically on **adaptation in coastal areas**, whereas the German Society for Technical Cooperation deals with specific practice-oriented requirements in relation to the ranking of adaptation measures in **developing countries** (GTZ, 2007). HALLEGATTE et al. (2008) create a conceptual framework which, against the background of different emissions scenarios, is aimed at supporting **cost-efficient adaptation strategies at the level of towns/cities**. Finally, FÜSSEL and KLEIN (2008) create guidelines for the **design and evaluation** of adaptation measures in the **health sector**.

112. HALLEGATTE (2011) creates a **7-stage guideline for drafting adaptation strategies** which focuses attention on the dynamic character of the adaptation process and thus provides room for flexibility and learning. The entire strategy development rests on climatic and economic scenarios which provide clues to the possible impacts of climate change and the appropriate adaptation measures. The aim then is to prioritise the measures identified using ranking methods (No. 60), paying special attention to urgency. In the process as many differ-

ent methods as possible should be applied in order to create the most objective and robust basis for decision making. For every selected measure an individual plan must be drawn up including specific verifiable success criteria or milestones which must be achieved by the measure according to a fixed timetable. The continuous monitoring enabled by this process is a requirement for the successful implementation of the measures. If the criteria are not met, corresponding modifications are to be made.

113. FÜSSEL (2007) describes **robust principles** to be taken into consideration when planning adaptation measures (see Table 6).

Necessary preconditions	Who should be involved?	Actual planning
Awareness of the problem: Assessing and communicating vulnerability to climate change. *Availability of effective adaptation measures*: Initiating research that may lead to the development of new adaptation options. *Information about these measures*: Identification and assessment of measures. *Availability of resources for implementing these measures*: Calculating co-benefits of the measures (→ increase in perceived benefit); Identifying ways to use resources efficiently, e.g. mainstreaming (→ reducing costs); motivating the provision of additional resources. *Cultural acceptability of the measures*: Educating the public about risks and response options → increasing the acceptability of unpopular measures. *Incentives for implementation*: Identifying barriers to implementation and approaches to overcome these barriers.	*Scientists*: Climate change (impacts) researchers deliver key information as to why current policies, practices and infrastructure may not be appropriate in the future. *Practitioners*: Actors who implement the recommended changes can share key information and experience which may be crucial for planning changes. *Decision-makers and other stakeholders*: Dual function: 1. By specifying priorities and criteria for "good" adaptation they help to design the assessment process. 2. They decide about the implementation of the changes recommended by the analysts. *Analysts with a political or economic background*: They help to prioritise the adaptation options on the basis of the expected benefits and costs (in a broad sense) or other criteria specified by the stakeholders.	The greater the *significance of climatic as opposed to non-climatic factors* for a particular decision, the greater the need for a detailed assessment of the risks associated with climate change. The better the *knowledge about future changes in climate risks*, the more specific the currently possible options are. The less *experience in dealing with a specific risk*, the greater the need for additional action. If *current climate risks are great*, the effective or efficient adaptation strategy is to address these risks primarily, taking future climatic changes into account. If *low-regret or no-regret measures* exist, the planned adaptation measure does not necessarily depend on reliable climate impact projections.

Table 6: Robust principles for effective planning of adaptation measures

114. A further category of guidelines concentrates on communicating to decision makers the **practical aspects** of the **application** of **procedures for ranking adaptation measures** (No. 60) or demonstrating their application on the basis of case studies. The focus here is on multi-criteria approaches. DE BRUIN et al. (2009c) present a holistic economics-based procedure for ranking adaptation measures, which they apply exemplarily to the Netherlands. This ex-

tends from the identification of appropriate adaptation measures and assessment criteria with the involvement of experts and stakeholders right through to the evaluation of measures which are essentially based on benefit-cost criteria. FÜSSEL (2009) criticises the one-sided orientation of this approach along the benefit-cost criterion and the associated methodological difficulties as well as its neglect of equity. He calls for a **multi-criteria approach**. SMITH and LENHART (1996) as well as SMITH (1997) develop an appropriate ranking system which, in addition to optimality, also takes other aspects such as flexibility and irreversibility into account. From a user- or practice-oriented perspective HALLEGATTE (2009) compares different selection procedures which are specifically aimed at prioritising **robust measures**. A further ranking-oriented approach is based on **risk management** instruments and methods (ECA, 2009).

115. Furthermore some guidelines cover **specific sub-areas** of adaptation policy or the adaptation process. PROWSE and SNILSTVEIT (2010) introduce **impact evaluation** as a possible procedure for evaluating measures that have already been implemented. It compares the welfare of the affected actors or region in the given situation (i.e. with the implemented measure) with their welfare in the hypothetical situation without the measure. SHARMA and SHARMA (2010) provide an introduction to the application of the **program-logic-approach**, which is used not only for evaluation but also for **monitoring purposes**. This involves modelling and graphically illustrating the logical connections between the available resources, the activities or measures, the stakeholders, and the outcomes of the respective adaptation problem. WHEELER (2011) develops guidelines for implementing cost-efficient allocations of **financial aid for adaptation**. GROTHMANN et al. (2009b) deal with the implementation and success monitoring of adaptation measures in the areas of **construction, living, transport and mobility**. Finally, **the integration of development and adaptation policy measures** has an important place in the relevant literature (GOKLANY, 2007, OECD, 2009 and GTZ, 2010).

8 Methodological Approaches in the Economics of Adaptation Research

116. This chapter provides an overview of the main methods applied in the individual research fields so that, if possible, conclusions can be drawn about promising but not yet established methodological approaches to certain thematic areas. The studies aimed at **documenting and defining the research area** (Chapter 2) are naturally conducted on a **verbal-argumentative level**, whereby various interdisciplinary approaches with sociological, political, economic, psychological and natural science components are noted (No. 6 ff.).

117. A broad mix of methods exists in the area of **climate adaptation goals** (Chapter 3). The process of defining economic goals is dominated by the **optimality or benefit-cost dogma** (Section 3.1.), whereas the thematic area of non-efficiency-related goals (Section 3.2), as well as the evaluation and selection of adaptation measures (Section 3.3.), is addressed using methods derived from a range of disciplines.

118. The optimality goal is supported methodologically within the framework of a **theoretical analysis** in the following way: **Static approaches** are dominated by **micro-economic optimisation approaches**, most of which are based on simple partial equilibrium models (Nos.

26, 27). With just one generally computable equilibrium model, **macro-economic studies** are clearly outnumbered (No. 29). To analyse the static trade-offs between adaptation and mitigation the **theory of endogenous risk** is used (No. 38). In the **dynamic analysis** the balance of forces between micro- and macro-economics works the other way around. Here there are only a small number of **micro-economics-based optimisation approaches** and **option value models** to be found (Nos. 30, 32, 39). Alongside macro-economic **growth models** (Nos. 33, 41), **Integrated Assessment Models** play a key role (Nos. 42-45).

119. In general, the efforts to provide an **empirical assessment of the benefits and costs of adaptation measures** appear to leave plenty of scope for development. On the benefit side only a few basic **conceptual considerations** have been undertaken (Nos. 47, 48). Most of the **cost estimates** are conducted using the **top-down** approach based on **physical climate models** in conjunction with **econometric methods** or on the basis of Integrated Assessment Models (No. 49). The numerous relevant **case studies** have been sharply criticised for exhibiting methodological limitations and fuzziness (No. 47). So far **bottom-up cost estimations** are the exception (No. 51).

120. The studies on **non-efficiency-related goals** are mostly of an **argumentative nature** and do not resort to model-based or formal methods (Section 3.2). Security of supply is the only goal which is sometimes examined within the framework of partial equilibrium models or coupled scientific-economic models (No. 55). Concerning the other relevant adaptation goals, various **different thinking approaches** are applied, most of which are **economical, sociological, political or interdisciplinary** in character (Nos. 52-54).

121. In the assessment and selection of adaptation measures decision-theoretic methods and above all benefit-cost-based and multi-criteria procedures dominate (No. 61-63). However numerous **other approaches** that have their origins in **economics** (e.g. game theory or public finance, No. 64, 65), **interdisciplinary** (e.g. Bayesian networks or the Tolerable Windows Approach, No. 65) or the **political and social sciences** (e.g. ethical and cultural decision rules or political role play and simulations, No. 65) are also taken.

122. The legitimisation of government intervention and the analysis of barriers to autonomous adaptation (Chapter 4) are based mainly on the (neo) classical **theory of market failure**. The occurrence and/or the effects of market failure are explored in a small number of **micro- and macroeconomic** approaches (or in Integrated Assessment Models) (No. 70). **Argumentative studies**, however, are in the majority. These studies are based on various economic theories and approaches (e.g. public finance aspects or principal agent theory), but they are not substantiated by models (Nos. 71-74). The same applies to studies on extended market failures. These work mainly with institutional, behavioural economics and also psychological methods (Nos. 75-78). Although the few studies on regulatory obstacles that exist are economics-oriented, they are not rooted in theory (Nos. 79-91). As to the fundamental barriers to autonomous adaptation, these are examined in interdisciplinary, argumentative treatises and field studies (Nos. 67, 68); in some cases interdisciplinary or natural science and economics models are also applied (No. 68). All of the studies dealing with the justification of government intervention via non-economic goals are argumentative and multi- or interdisciplinary in character (No. 82).

123. It is remarkable that the studies on **adaptation governance and instrument choice** (Chapter 5) completely forego any formal, model-based analyses. The documentation of potential and existing instruments and institutions takes place on the basis of **theoretical** economic, and in part interdisciplinary **considerations** (Nos. 85-88) on the one hand, and with the help of **field studies** (Nos. 89-91) on the other. Field studies, but also **institutional economics approaches**, are similarly used to identify and analyse **barriers to public adaptation** (Nos. 93-97). In this context the highly promising theoretical framework of **Public Choice** in only used explicitly in one study (No. 94). The **normative analysis** of adaptation governance is essentially rooted in institutional economics (Nos. 98-102).

124. When it comes to studying the role of adaptation in **international agreements on greenhouse gas reductions, game theory models** are the dominant instrument (Chapter 5). In some cases partial equilibrium models or experimental analyses complement the studies (Nos. 108, 109).

125. The **guidelines** for political decision makers are derived from broad-based interdisciplinary considerations of a qualitative nature (Chapter 7), but they are sometimes supported by **decision-theoretical methods** (No. 114).

126. **Bayesian networks** and **Agent Based Models** have, to some extent, a cross-sectional function (No. 51). As they are particularly useful for modelling the characteristic massive uncertainty or the complex actor and decision structure, they can, in principle, be used for most of the research fields described here. However it is mainly their application potential in climate adaptation that is discussed in the literature although, judging by the current state of the research, concrete applications are yet to be found.

9 Key Issues in Adaptation Research and Policy

127. The aim of this chapter is to identify the **thematic priorities in the research into the economics of adaptation** and also to examine how these objectives are reflected in **adaptation policy**. This should allow the drawing of careful conclusions about the political relevance of economic research and about potential action requirements in the area of scientific policy advice. The relative importance of the **different sets of research themes** can be quantitatively estimated by comparing the respective number of publications, see Figure 8.[15] This shows that the definition of goals, followed closely by governance and choice of instruments, are the most prominent topics in the research into the economics of adaptation. In comparison, barriers to autonomous adaptation, legitimisation of government intervention and the development of guidelines play a more subordinate role. The lowest number of contributions is found in the area of the importance of adaptation for international climate protection agreements. The distribution of topics is of course determined by several factors, but the most important one are most likely the complexity of the respective topic, the availability and sophistication of appropriate methods as well as the priorities set in the areas of research

[15] The relative importance of a thematic area is determined by the number of scientific contributions in the respective area in proportion to the total number of contributions in all thematic areas, bearing in mind that one contribution can refer to several thematic areas.

policy and funding. However a more in-depth exploration of this question goes beyond the scope of this report.

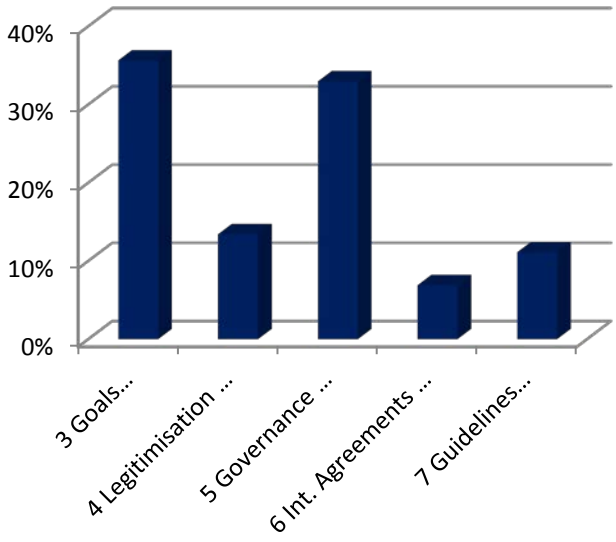

Figure 8: Thematic Priorities in the Economics of Adaptation Research

128. The **importance of economic research priorities in adaptation policy** can be evaluated on the basis of a comparison of national adaptation strategies. In this regard the PEER (2009) study provides an **initial point of reference** which includes a comprehensive, comparative evaluation of the **adaptation strategies of the European countries**. The study takes a **holistic approach**, i.e. in addition to examining the importance of findings from (economic) adaptation research, general determinants relating to the establishment and development of the strategies, the interaction between science and policy, the communication of information related to adaptation, the role of multi-level governance, the integration of adaptation in sectoral policy as well as the monitoring, evaluation and implementation of adaptation policy measures are studied. Figure 9 provides an overview of the evaluation of these national strategies. The **following key results emerge in relation to the importance of adaptation research**: In all countries scientific findings have provided the basis for developing strategies. The orientation and content of these strategies were shaped largely by scientific data on the workings of the climate system, the consequences of climate change and vulnerabilities. The costs of adaptation, above all, were at the centre of attention in the economic studies.

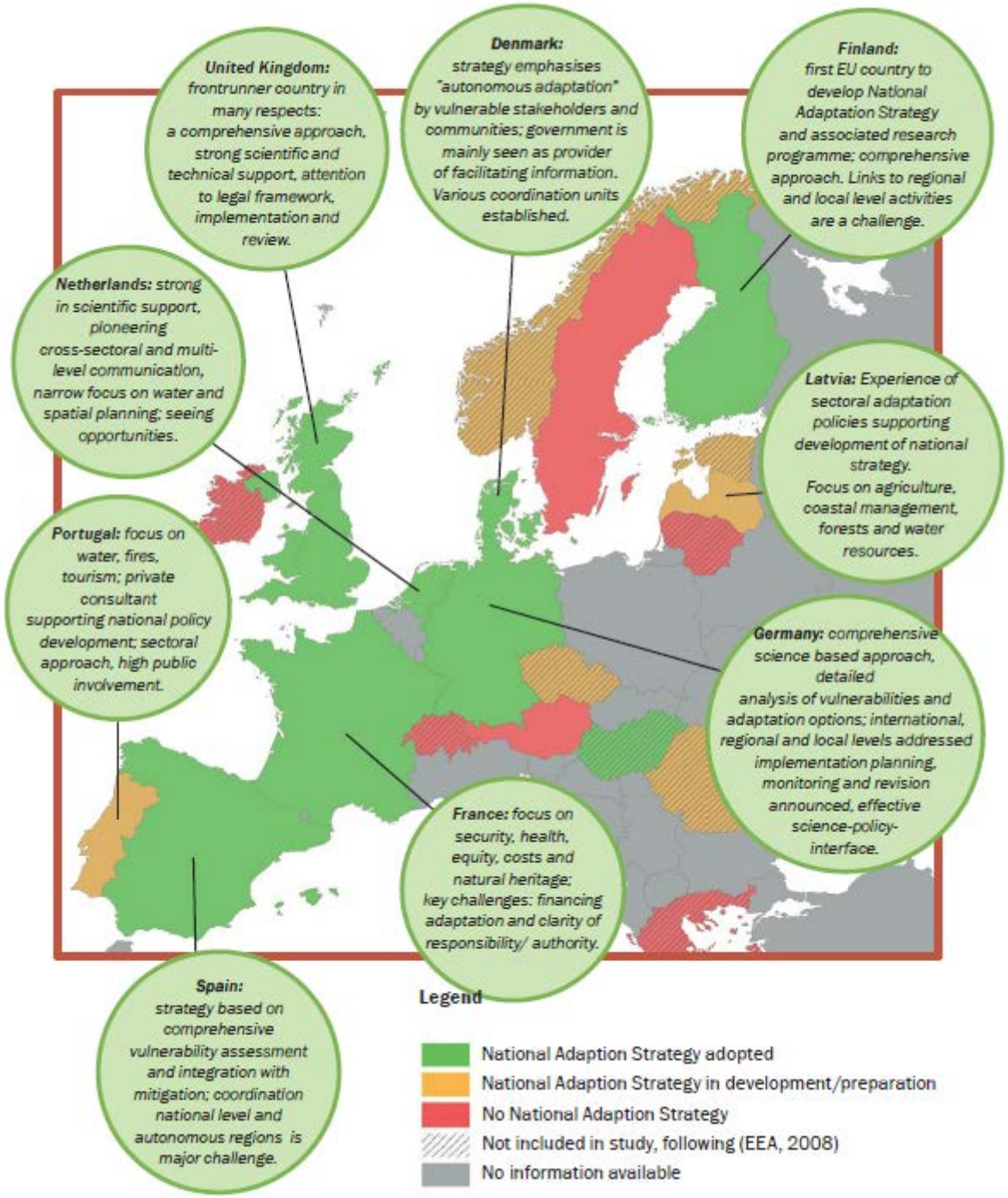

Figure 9: A Comparison of National Adaptation Strategies in Europe (PEER, 2009)

129. To gain a better **insight into the significance of the thematic priorities in the economics of adaptation research for adaptation policy**, in comparison to the holistic approach taken by PEER (2009), the German Strategy for Adaptation to Climate Change (DAS) and the corresponding Adaptation Action Plan are exemplarily examined in the following with

regard to this question (BMU, 2008 and 2011). According to the PEER (2009) study, this strategy is essentially representative of the strategies of the European countries with the strongest economies. When it comes to **defining and implementing goals**, the genuine purpose of the adaptation – reducing vulnerability – has so far been the main focus. To date there is no recognisable system for prioritising and selecting measures (GAWEL and HEUSON, 2011). However the relevance of efficiency or the benefit-cost criterion is by all means acknowledged in this context and the initiation of various research projects to close the relevant knowledge and information gaps, particularly in relation to regional and sectoral adaptation measures, is recommended. The pursuit of ecological goals and security of supply can only be identified, if at all, indirectly, in efforts to establish cross-links to other strategy processes (e.g. biodiversity) or appointed measures, e.g. adaptation in the energy sector. The aspect of equity plays a role only at international level in the context of adaptation funding. However there is no targeted method for pursuing multiple goals on the basis of economic or decision theory approaches.

130. Research on the **barriers to autonomous adaptation** has been considered in policy-making, insofar as all of the government interventions set out in the national strategy or in the action plan are **legitimate from the standpoint of economics**. However, the individual barriers, e.g. behavioural obstacles, are not specifically addressed. The field of **governance and instrument choice** is given little to no attention in the DAS. In particular, aspects of multi-level governance such as the coordination of various government interventions are completely left out. The same applies to research into **the implications of adaptation for international climate protection agreements**.

131. **To sum up**, it can be said that although research efforts are being initiated to ensure the adaptation process is based on sound economic foundations, so far it is the scientific findings on climate change impacts and vulnerability that have actually shaped the conceptualisation of the German adaptation strategy and the concretisation of the first measures. This can be explained on the one hand by the fact that adaptation has only made it on to the political agenda in the last few years as a complementary strategy to mitigation. As a consequence, the adaptation process is in a very early stage and so, at the moment, it is primarily focussed on the main purpose of adaptation. On the other hand, part of the responsibility for the low impact of economic research on the DAS and the Adaptation Action Plan has to be attributed to the fact that communication between science and politics is not yet fully developed.

10 The German Research Landscape

132. Before closing with a final chapter on key pointers for the future research, this chapter presents a **brief outline of the current research landscape in Germany**. Adaptation research plays a clearly subordinate role in the **universities**, in comparison with the research institutes. The **Chair of Environment and Development Economics at the University of Oldenburg** is the only one explicitly established to focus on climate adaptation. The primary focus is on the adaptation instruments employed in strongly regulated sectors with long-lasting infrastructure, such as the energy or transport sectors. The research takes an interdisciplinary approach and is supported by physical, economic or political theories, among

others. In terms of methodology, both qualitative and mathematical modelling approaches are used. On the basis of a cooperation with the **Institute for Ecological Economic Research (IÖW)** Berlin the **Chameleon Research Group** is affiliated to the Chair. This group focuses its attention on climate adaptation in public service companies and on the development and analysis of appropriate policy response options.

133. In most of the economic research institutes the topic of adaptation has been established – albeit not according to specific research priorities. The **Centre for European Economic Research (ZEW)** in Mannheim deals with topics such as the integrated economic assessment of adaptation instruments, the fiscal effects of adaptation measures, conceptual issues surrounding the legitimisation of and need for government intervention, and behavioural barriers to autonomous adaptation. In addition to the more prominent quantitative, empirical methods financial and experimental approaches are also used in the process. The **German Institute for Economic Research (DIW)** in Berlin is concerned with individual selected questions such as e.g. adaptation funding in developing countries, the development of mitigation and adaptation strategies within the framework of European climate policy or the assessment of the costs and benefits of adaptation measures. Here too, quantitative empirical methods are in the foreground. Regional adaptive capacity and the economic assessment of regional adaptation measures is the subject of research at the **Hamburg Institute of Global Economics (HWWI)**. The research is carried out using empirical-quantitative and theoretical models as well as simulation analyses based on these. The **Cologne Institute for Economic Research (IW)** deals with i.a. conceptual issues surrounding the importance of international cooperation in the area of climate adaptation as well as sectoral adaptation instruments and measures. The **Kiel Institute for the World Economy (IFW)** examines climate adaptation processes within the framework of the research area “Environment and Natural Resources”, whereby a particular focus is placed on quantifying adaptation costs in the healthcare sector.

134. Furthermore, various **interdisciplinary research institutions** also tackle economic questions of adaptation. In the context of its climate research programme the **Department of Economics at the Helmholtz Centre for Environmental Research – UFZ** in Leipzig examines questions related to specific aspects of adaptation in close cooperation with the other social science departments at the UFZ (Environmental and Planning Law, Urban and Environmental Sociology, Environmental Politics). One priority is the development of participatory decision support tools for the choice of adaptation measures under uncertainty, which can be applied in areas such as flood management. Another input for the choice of measures is provided in the form of natural hazard cost assessments, which determine the benefit of the respective adaptation measures. The second major research priority deals with questions of governance and instrument choice. More specifically, the aim here is to identify the synergies and conflicts of adaptation measures and instruments, and to identify and overcome potential barriers to autonomous and public adaptation. A broad mix of methods is applied to tackle these questions. These include software-based, decision-theoretical approaches, financial approaches (e.g. theory of public goods, theory of federalism, public choice theory) as well as New Institutional Economics concepts (economic analysis of law, social contract theory, theory of property rights, transaction cost theory) and game theory. The **Potsdam Institute for Climate Research (PIK)** pursues a trans-disciplinary approach which, set in the larger context of sustainability, analyses the relationship between mitigation and adaptation, land

use, use of resources and general socio-economic development. The design and assessment of adaptation policy guidelines also plays an important role. Most of the research projects are behaviour-, region- (Europe) and sector-specific (agriculture, health). Integrated Assessment Models and related modelling approaches provide the key instruments for analysis. Also at the **Ecologic Institute** in Berlin, where various approaches from the social sciences are brought together for research purposes, the economics of adaptation research occupies a key position. The relevant projects comprise mostly regional and sectoral studies on the economic assessment of adaptation measures as well as the design and evaluation of adaptation projects and strategies, but also aspects of international adaptation funding aid and adaptation cooperation. Lastly, the **Fraunhofer Institute for Systems and Innovation Research (ISI)** in Karlsruhe pursues a systematic, interdisciplinary approach, focussed mainly on the design of European adaptation and mitigation strategies as well as the quantification of the benefit and costs of adaptation measures.

135. Finally, within the framework of its "**Economics of Climate Change**" funding programme the **German Federal Ministry of Education and Research (BMBF)** has initiated a range of projects related to adaptation, which are being carried out both in university and non-university research institutions:[16]

- Regional economic evaluation of adaptation measures in agricultural, forestry and bioenergy production under the influence of climate change (REGECON) – **University of Bayreuth**;
- Climate change mitigation and adaptation under uncertainty (CLIMA-U) – **IfW**;
- Evaluating Measures on Climate Protection and Adaptation to Climate Change in Agglomerations (EMPACCA) – **HWWI** and **TU Dresden**;
- Climate Service Centre: Development of a national service centre for communicating knowledge about climate and climate change in the form of needs-based products to decision makers in politics, the economy and society – **Helmholtz-Centre Geesthacht for Materials and Coastal Research (HZG)**;
- Joint project: Regional Adaptation Strategies for the German Baltic Sea Coast (RADOST), Sub-project 8: Socioeconomic analysis of regional strategies for adaptation to climate change – **IÖW**.

136. Overall it can be said that **the research on the economics of adaptation in Germany is mainly application-oriented with a strong regional and sectoral focus**. The focus of the research is above all on the economic assessment of adaptation measures. Basic conceptual studies on the definition of goals and the selection of instruments, overcoming barriers to autonomous adaptation or governance and instrument choice play a relatively minor role.

11 Key Pointers for Future Research

137. Based on the overall review of the literature this chapter assumes the task of sketching an outline for the future direction of the research into the economics of climate adaptation, whereby, in line with the approach of this report, the focus is placed on **conceptual re-**

[16] Detailed information on the "Economics of Climate Change" funding programme can be found at www.bmbf.de/foerderungen/14682.php.

search. For this purpose the individual research fields are examined with regard to their potential for promising **open research questions**. On the one hand the results of the literature review play an important role. But the potential is also measured according to whether the respective research approach is politically relevant and meets a corresponding "demand" (Chapter 9).

138. Although the **documentation and definition of the research area** (Chapter 2) is not in itself of direct political relevance, it does form the basis for all further research efforts. The work on the definitions and the dimensions of climate adaptation as well as other preliminary considerations is basically fully mature and relatively well advanced. However, there is a certain amount of confusion or inconsistency here, so that without a doubt there is **some potential for synthesising**, organising and possibly also modifying or adding to the current conceptions.

139. Given the early stage of the political adaptation process there is a very **great need for research results to identify and realise efficiency- and non-efficiency-related aims** (Chapter 3), especially since the appointed policy measures have so far concentrated on reducing vulnerability and are therefore primarily based on findings from the natural sciences. Due to the broad scope of this field of research, the potential for new approaches must be considered in a differentiated way.

140. The works dealing with the **optimality goal** (Section 3.1) are subdivided into **theoretical** (Section 3.1.1) and empirical approaches (Section 3.1.2). In the case of the former it is important to distinguish between isolated assessments of adaptation (Section 3.1.1.1) and integrated assessments of adaptation and mitigation (Section 3.1.1.2). The studies on optimal adaptation considered in isolation are based on solid conceptual and model-theoretical foundations – this applies to both static and dynamic assessments. When it comes to the model-theoretical approaches, it is important to note that the inherent massive uncertainty of the adaptation process can only be reflected insufficiently, if at all, according to expected utility theory. Also, the aspects of irreversibility and the possibility of learning are largely left out of these models. Concerning static integrated assessments of adaptation and mitigation it is evident that basic questions relating to potential synergies and conflicts between these two strategies are examined, however, they are not merged into a holistic conceptual framework let alone be reproduced in a model-theoretical framework. **Dynamic integrated assessments** are dominated by Integrated Assessment Models (Nos. 42-45). The literature on the integration of adaptation in this model class already displays considerable scope and continues to grow at a rapid pace. Nevertheless, there is still a huge need for action in terms of the adequate representation of adaptation in Integrated Assessment Models to enable the provision of practice-relevant policy recommendations. This applies mainly to the bottom-up character of adaptation, the fact that it is bound to the local or regional context, the particularly pronounced uncertainly as well as the limited rational adaptation behaviour of the respective actors.

141. Furthermore, **besides Integrated Assessment Models, some isolated integrated dynamic modelling approaches** do exist which are grounded in micro- or macro-economics (Nos. 39-41). When it comes to the microeconomic approaches, a deeper analysis of the questions relating to uncertainty, learning and the limited rational behaviour of the adaptation

actors would be desirable with regard to providing policy advice. The macroeconomic approaches essentially face the same challenges as the Integrated Assessment Models.

142. For obvious reasons the **empirical assessment of the benefit and costs of adaptation** is of the utmost relevance for decision makers in adaptation policy. The relevant works consist almost exclusively of applied benefit-cost analyses or econometric methods within the framework of case studies. Conceptual deliberations on climate-specific (methodological) assessment problems, particularly on the benefit side, are the exception (Nos. 47, 50), and thus represent a starting point for future research. Of special significance here is the question of basic methodological orientation of assessment procedures. Although the **top-down** approaches promise to deliver cost estimates at an acceptable level of input, they are too inaccurate when applied to the local or regional level at which the adaptation decisions are made. The exact opposite is the case for **bottom-up** methods. They enable relatively accurate estimates of local and regional adaptation costs, but are too costly to be implemented extensively. Given this trade-off, there is a need to determine whether the two methods can be meaningfully combined or integrated.

143. As for the works on **other, non-efficiency-related aims** (Section 3.2), it can be stated that although there is also a certain potential for synthesis, the fundamental conceptual questions have been addressed. However, how the respective aims can be operationalised is in many cases still unclear. Even model-based studies, which can potentially deliver interesting information, are not applied. Furthermore, the **security policy dimension** of adaptation policy is also pointed out. The reason behind this is that adaptation measures can prevent violent conflict that may emerge from (climate change-induced) migration movements or scarcity of resources. Even though this topic has received little attention to date, it is certainly promising while at the same time being, at least in the mid- to long-term, of significant political relevance.

144. By contrast, the research on the **assessment and choice of adaptation measures** (No. 56 ff.) is of exceptional importance for the current stage of adaptation policy in which strategies and the first sets of measures are being designed. Although economic theory offers a hotchpotch of relevant methods, their systematic application in practice is not evident – this applies in particular to multi-criteria methods that can be used to pursue multiple goals. Thus there is a requirement here for research to detect and remove potential obstacles to the application of these methods. In addition to creating or developing the possibilities for stakeholders and decision makers to participate, better communication of these procedures could also play a major role.

145. Research into the barriers to **autonomous adaptation and the legitimisation of government intervention** (Chapter 4) is basically well developed and is both conceptually and model-theoretically substantiated and is also being taken into account in politics. This applies in particular to the classical forms of market failure (Nos. 70-74). Even though possible institutional, regulatory, organisational or behavioural barriers are mentioned in the literature, they are not analysed in any great detail. The application of methods derived from institutional economics or behavioural economics appears very promising here.

146. The topic of **governance and instrument choice** (Chapter 5) is of exceptional importance in the research, but so far it has only attracted limited attention from politicians, which, given the objective relevance of the topic, may indicate a communication problem on the part of the scientists. Future research efforts should take this aspect into account. The **conceptual documentation and systematisation of government adaptation instruments** (Section 5.1) is already being carried out in an exemplary manner, leaving scarcely any questions open (Nos. 85-88).

147. In contrast, the conceptual research into **barriers to public adaptation** (Section 5.2) leaves scope for development in many respects. Although the fundamental barriers are identified in the literature (Nos. 92-97), there is no existing holistic organisation or a deeper analysis, let alone a model-based record of these considerations. It is also quite remarkable that only one study considers these questions from the Public Choice perspective, despite the fact that this most certainly represents a very promising approach.

148. When it comes to the **normative analysis of adaptation governance** (Section 5.3) basically the same conclusions apply as for barriers to public adaptation (No. 147). However, one point sticks out: Although it is mentioned time and again in the literature that adaptation serves not only to avert climate damage, but also to use the potential advantages of climate change, **climate change winners** play no role in the deliberations on adaptation governance. In this context, interesting open research questions are sure to be found, e.g. in relation to the instruments for adaptation funding aid or burden sharing.

149. Research on the **importance of adaptation for international climate protection agreements** (Chapter 6) is still a very young field, although it already comprises a sizeable number of works. Possibilities for expansion are given in many respects. But the most promising – also with regard to political relevance – are the efforts to integrate institutional framework conditions and restrictions, such as e.g. funds or other instruments of international adaptation funding aid, into the analysis.

150. The development of **guidelines** (Chapter 7) for designing and implementing adaptation policy, although of great political importance, is not per se the subject of conceptual adaptation research. The same does not apply to theoretical and empirical **exploration of the determinants of the application and success of the guidelines as well as the evaluation of adaptation programmes**. However, so far, virtually no contributions have been identified in this area.

151. **Overall** it has been shown that a variety of challenges exist for open research questions of a conceptual nature. In view of the current political relevance, questions surrounding the definition or realisation of goals as well as the assessment and selection of adaptation measures should be given priority. Here the aim is also to come to **fundamental methodological decisions**: The **benefit-cost paradigm** which dominates the research is given a great deal of attention in the political arena – although not yet systematically in the design of interventions and measures – but in the form of political recommendations derived from Integrated Assessment Models. Nevertheless, this class of model suffers from glaring inherent weaknesses and shortfalls in relation to the adequate representation of characteristic adaptation features such as heterogeneity, bottom-up character, uncertainty and its local or regional

context constraints. Even if further intensive research efforts were to alleviate these weaknesses, whether and to what extent this approach can ultimately serve as an appropriate tool for providing practical policy advice is questionable. A key task of the research into the economics of adaptation is therefore to design alternative, **practical approaches to support decision making**, which can by all means maintain the benefit-cost criterion as an orientation aid or reference point. Prioritising the robustness and flexibility criteria and the insurance-theoretical recording of the adaptation problem represent the first steps in this direction.

Appendix: A Game Theory Analysis Framework for Exploring the Optimal Adaptation-Mitigation Mix

(according to SCHWARZE et al., 2012)

Basic model

Two identical countries $i = 1,2$ can confront climate change by means of mitigation (m_i) and adaptation (a_i). Both measures incur costs $c_i(m_i)$ or $c_i(a_i)$ with $\frac{dc_i(m_i)}{dm_i} > 0$, $\frac{d^2c_i(m_i)}{dm_i{}^2} > 0$ or $\frac{dc_i(a_i)}{da_i} > 0$, $\frac{d^2c_i(a_i)}{da_i{}^2} > 0$, $\forall\, i = 1,2$. It should be noted that the adaptation is anticipatory, i.e. the adaptation costs are incurred irrespective of whether or not the damage actually occurs.
The mitigation service of country i reduces the global probability $p(m_1, m_2)$ of occurrence of the climate-induced damage (self-protection), i.e. $\frac{\partial p(m_1,m_2)}{\partial m_i} < 0$, with $\frac{\partial^2 p(m_1,m_2)}{\partial m_i{}^2} > 0$, $\forall\, i = 1,2$ (diminishing marginal return of the mitigation), and therefore represents a (global) public good. In contrast, adaptation is a private good, i.e. the adaptation effort of country i reduces only its own (residual) damage $s_i(a_i)$ ("self-insurance"), but leaves that of the other country untouched: $\frac{ds_i(a_i)}{da_i} < 0$, with $\frac{d^2s_i(a_i)}{da_i{}^2} > 0$ (diminishing marginal returns from the adaptation), $\forall\, i = 1,2$.

Cooperative equilibrium

Both risk-neutral countries minimise the expected total global costs, which comprises the sum of their mitigation, adaptation and expected damage costs, across the four control variables m_1, m_2, a_1, a_2:

$$\min_{\{m_{i=1,2}, a_{i=1,2}\}} C(m_1, m_2, a_1, a_2) = c_1(m_1) + c_2(m_2) + c_1(a_1) + c_2(a_2) + p(m_1, m_2)\big(s_1(a_1) + s_2(a_2)\big) \quad (1)$$

The respective first-order conditions are:

$$\frac{\partial C(\cdot)}{\partial m_1} = \frac{dc_1(m_1)}{dm_1} + \frac{\partial p(m_1,m_2)}{\partial m_1}\big(s_1(a_1) + s_2(a_2)\big) = 0 \Leftrightarrow \frac{dc_1(m_1)}{dm_1} = -\frac{\partial p(m_1,m_2)}{\partial m_1}\big(s_1(a_1) + s_2(a_2)\big) \quad (2)$$

$$\frac{\partial C(\cdot)}{\partial m_2} = \frac{dc_2(m_2)}{dm_2} + \frac{\partial p(m_1,m_2)}{\partial m_2}\big(s_1(a_1) + s_2(a_2)\big) = 0 \Leftrightarrow \frac{dc_2(m_2)}{dm_2} = -\frac{\partial p(m_1,m_2)}{\partial m_2}\big(s_1(a_1) + s_2(a_2)\big) \quad (3)$$

$$\frac{\partial C(\cdot)}{\partial a_1} = \frac{dc_1(a_1)}{da_1} + p(m_1, m_2)\frac{ds_1(a_1)}{da_1} = 0 \Leftrightarrow \frac{dc_1(a_1)}{da_1} = -\,p(m_1, m_2)\frac{ds_1(a_1)}{da_1} \quad (4)$$

$$\frac{\partial C(\cdot)}{\partial a_2} = \frac{dc_2(a_2)}{da_2} + p(m_1, m_2)\frac{ds_2(a_2)}{da_2} = 0 \Leftrightarrow \frac{dc_2(a_2)}{da_2} = -\,p(m_1, m_2)\frac{ds_2(a_2)}{da_2} \quad (5)$$

(2) and (3), the conditions for optimal mitigation of the two countries, say that the marginal costs and the expected marginal utility of mitigation (expected global marginal damages

saved) must be balanced. The analogous condition applies to the optimal country-specific adaptation efforts according to (4) and (5).

Non-cooperative equilibrium

Here only the countries' own costs are included in the minimisation problem for the respective country – as exemplarily illustrated in the following for Country 1:

$$\min_{\{m_1,a_1\}} C_1(m_1,m_2,a_1) = c_1(m_1) + c_1(a_1) + p(m_1,m_2)s_1(a_1) \tag{6}$$

The following two first-order conditions result:

$$\frac{\partial C_1(\cdot)}{\partial m_1} = \frac{dc_1(m_1)}{dm_1} + \frac{\partial p(m_1,m_2)}{\partial m_1}s_1(a_1) = 0 \Leftrightarrow \frac{dc_1(m_1)}{dm_1} = -\frac{\partial p(m_1,m_2)}{\partial m_1}s_1(a_1) \tag{7}$$

$$\frac{\partial C_1(\cdot)}{\partial a_1} = \frac{dc_1(a_1)}{da_1} + p(m_1,m_2)\frac{ds_1(a_1)}{da_1} = 0 \Leftrightarrow \frac{dc_1(a_1)}{da_1} = -p(m_1,m_2)\frac{ds_1(a_1)}{da_1} \tag{8}$$

A comparison of (7) and (2) shows that Country 1 considers only its own (residual) damage, whereas in the cooperative setting the calculation is performed with the global damage. As a result of the public-good character of mitigation, from a global welfare perspective, Country 1 mitigates too little, since it neglects the effect of its emissions reduction on the expected damage of Country 2.
In contrast, (8) is completely in agreement with (4) because in the case of adaptation we are dealing with a private good. However, since m_1 enters into (8) the adaptation service is suboptimal – in concrete terms, it is sub-optimally large because m_1 is sub-optimally small.

On the **strategic interaction** between the countries (see below for proof and a detailed explanation):

- $\frac{dm_1}{dm_2}$: The mitigation response of Country 1 to a marginal increase in the mitigation effort of Country 2 is essentially dependent on the cross-derivative $\frac{\partial^2 p(m_1,m_2)}{\partial m_1 \partial m_2}$. This demonstrates how significantly a marginal increase in m_2 can diminish the marginal returns of the mitigation of Country 1. If $\frac{\partial^2 p(m_1,m_2)}{\partial m_1 \partial m_2}$ is large enough, then as expected free-rider behaviour will result, i.e. $\frac{dm_1}{dm_2} < 0$. However, depending on the extent of the cross-derivative $\frac{dm_1}{dm_2} = 0$ or $\frac{dm_1}{dm_2} > 0$ is also possible.
- $\frac{da_1}{dm_2}$: The adaptation response of Country 1 to a marginal increase in the mitigation service of Country 2 also depends on the aforementioned cross-derivative. Here $\frac{da_1}{dm_2} < 0$ requires that $\frac{\partial^2 p(m_1,m_2)}{\partial m_1 \partial m_2}$ is sufficiently small.
- a_2, as a “private good” for Country 2, plays no role in the calculation of Country 1. Hence the following applies: $\frac{dm_1}{da_2} = \frac{da_1}{da_2} = 0$.

The simultaneous solution of (7) and (8) as well as the corresponding profit-maximising conditions for Country 2 yields the mitigation and adaptation quantities of both countries in the non-cooperative Nash equilibrium. An explicit solution is not possible without specifying the functions.

Proof of strategic interaction:

Comparative static analysis (see e.g. GRAVELLE and REES, 2004, pp. 696 ff.):

- $\frac{dm_1}{dm_2} = \frac{\det H_{m_1 m_2}}{\det H}$, whereby

H denotes the Hessian matrix of the minimisation problem (6), with

$$H = \begin{pmatrix} \partial^2 C_1(\cdot)/\partial {m_1}^2 & \partial^2 C_1(\cdot)/\partial m_1 \partial a_1 \\ \partial^2 C_1(\cdot)/\partial a_1 \partial m_1 & \partial^2 C_1(\cdot)/\partial {a_1}^2 \end{pmatrix}$$

The existence of a global minimum for (6) requires that H be positively definite, such that $\det H > 0$ must apply (however, this does not emerge from model assumptions: all 4 components of H are positive).
One arrives at the matrix $H_{m_1 m_2}$ by substituting the first column with the column vector $(-\partial^2 C_1(\cdot)/\partial m_1 \partial m_2\,,\quad -\partial^2 C_1(\cdot)/\partial a_1 \partial m_2)$. The result for the corresponding determinant is

$$\begin{aligned} \det H_{m_1 m_2} &= \det \begin{pmatrix} -\partial^2 C_1(\cdot)/\partial m_1 \partial m_2 & \partial^2 C_1(\cdot)/\partial m_1 \partial a_1 \\ -\partial^2 C_1(\cdot)/\partial a_1 \partial m_2 & \partial^2 C_1(\cdot)/\partial {a_1}^2 \end{pmatrix} \\ &= \det \begin{pmatrix} -\dfrac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} s_1(a_1) & \dfrac{\partial p(\cdot)}{\partial m_1} \dfrac{ds_1(a_1)}{da_1} \\ -\dfrac{\partial p(\cdot)}{\partial m_2} \dfrac{ds_1(a_1)}{da_1} & \dfrac{d^2 c_1(a_1)}{d{a_1}^2} + p(\cdot) \dfrac{d^2 s_1(a_1)}{d{a_1}^2} \end{pmatrix} \end{aligned}$$

From the model assumptions, the following signs result for the four components of the matrix: $\begin{pmatrix} a? & b>0 \\ c<0 & d>0 \end{pmatrix}$. $\det H_{m_1 m_2} = ad - cb$. $\operatorname{sgn}\{\det H_{m_1 m_2}\} = \operatorname{sgn}\left\{ \underbrace{ad}_{?} - \underbrace{cb}_{\substack{\leq 0 \\ >0}} \right\}$.

The signs of b, c and d are clearly fixed. Only the sign of the cross-derivative in component a is not defined. However, due to the global public-good character of mitigation m_1 and m_2 are assumed to be perfect substitutes. Hence, it follows directly from the law of diminishing returns that $\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} > 0$, which in turn determines: $a < 0 \Rightarrow \operatorname{sgn}\{\det H_{m_1 m_2}\} = \operatorname{sgn}\left\{ \underbrace{ad}_{<0} - \underbrace{cb}_{\substack{\leq 0 \\ >0}} \right\}$.

Hence overall the following 3 cases are possible:

$$\frac{dm_1}{dm_2}\begin{cases} < 0 \Leftrightarrow \det H_{m_1 m_2} < 0 \ (i) \\ = 0 \Leftrightarrow \det H_{m_1 m_2} = 0 \ (ii) \\ > 0 \Leftrightarrow \det H_{m_1 m_2} > 0 \ (iii) \end{cases}$$

Case (i)

$\det H_{m_1 m_2} < 0 \Rightarrow |ad| > |cb|$; i.e. $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ must be sufficiently large. This means that a marginal increase in the mitigation service of Country 2 must diminish the marginal returns of mitigation of Country 1 sufficiently strongly. This is the case provided the total mitigation starting level is relatively small.

Interpretation of the of the first-order conditions (7) and (8):

Direct effects:

(7): $m_2 \uparrow$ lowers the marginal returns of the mitigation $\frac{\partial p(\cdot)}{\partial m_1}$ (RHS). Thus this option also demands lower marginal costs (LHS), i.e. $m_1 \downarrow$.
(8): $m_2 \uparrow$ reduces the weighting of the marginal returns from the adaptation (RHS). Thus this option also demands lower marginal costs (LHS), i.e. $a_1 \downarrow$ (→ indirect relevance for $\frac{dm_1}{dm_2}$ over indirect effect).

Indirect effect (considering that (7) and (8) must be solved simultaneously)**:**

$a_1 \downarrow$ causes via (7) an increase in the weighting of the marginal returns from the mitigation and hence $m_1 \uparrow$.

Thus the indirect effect counteracts the direct effect. The latter is stronger when $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ is sufficiently large. In concrete terms, the following must apply:

$$ad - cb < 0 \Rightarrow \frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} > \frac{\frac{\partial p(\cdot)}{\partial m_2}\frac{ds_1(a_1)}{da_1}\frac{\partial p(\cdot)}{\partial m_1}\frac{ds_1(a_1)}{da_1}}{s_1(a_1)\left(\frac{d^2 c_1(a_1)}{da_1{}^2} + p(\cdot)\frac{d^2 s_1(a_1)}{da_1{}^2}\right)} > 0$$

Case (ii)

$\det H_{m_1 m_2} = 0 \Rightarrow |ad| = |cb|$; interpretation as in Case (i); $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ in such a way that the direct and indirect effects just neutralise each other.

Case (iii)

$\det H_{m_1 m_2} > 0 \Rightarrow |ad| < |cb|$ → see interpretation above.

- $\frac{da_1}{dm_2} = \frac{\det H_{a_1 m_2}}{\det H}$, whereby

one arrives at the matrix $H_{a_1 m_2}$ by substituting the second column of the Hessian matrix with the column vector $(-\partial^2 C_1(\cdot)/\partial m_1 \partial m_2\,,\quad -\partial^2 C_1(\cdot)/\partial a_1 \partial m_2)$. The result for the corresponding determinant is

$$\det H_{a_1 m_2} = \det\begin{pmatrix} \partial^2 C_1(\cdot)/\partial {m_1}^2 & -\partial^2 C_1(\cdot)/\partial m_1 \partial m_2 \\ \partial^2 C_1(\cdot)/\partial a_1 \partial m_1 & -\partial^2 C_1(\cdot)/\partial a_1 \partial m_2 \end{pmatrix}$$
$$= \det\begin{pmatrix} \frac{d^2 c_1(m_1)}{d{m_1}^2} + \frac{\partial^2 p(\cdot)}{\partial {m_1}^2} s_1(a_1) & -\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} s_1(a_1) \\ \frac{\partial p(\cdot)}{\partial m_1}\frac{d s_1(a_1)}{d a_1} & -\frac{\partial p(\cdot)}{\partial m_2}\frac{d s_1(a_1)}{d a_1} \end{pmatrix}$$

From the model assumptions the following signs result for the four components of the matrix: $\begin{pmatrix} a>0 & b? \\ c>0 & d<0 \end{pmatrix}$. Not clearly defined is b, or the sign of the cross-derivative $\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}$. However, on the grounds mentioned above it can be assumed that $\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} > 0$, from which follows$b <$ lows$b < 0 \Rightarrow \operatorname{sgn}\{\det H_{a_1 m_2}\} = \operatorname{sgn}\left\{\underbrace{ad}_{<0} - \underbrace{\underbrace{cb}_{\leq 0}}_{>0}\right\}$. Hence, in general the following 3 cases are possible:

$$\frac{da_1}{dm_2}\begin{cases} < 0 \Leftrightarrow \det H_{a_1 m_2} < 0\ (i) \\ = 0 \Leftrightarrow \det H_{a_1 m_2} = 0\ (ii) \\ > 0 \Leftrightarrow \det H_{a_1 m_2} > 0\ (iii) \end{cases}$$

Case (i)

$\det H_{a_1 m_2} < 0 \Rightarrow |ad| > |cb|$; i.e. $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ must be sufficiently small. This means that a marginal increase in the mitigation effort of Country 2 must diminish the marginal returns of the mitigation of Country 1 sufficiently weakly. This is the case provided the total mitigation starting level is relatively large.

Interpretation via the first-order conditions (8) and (7):

Direct effects:

(8): $m_2 \uparrow$ lowers the weighting of the marginal return of the adaptation (RHS). Thus this option demands lower marginal costs (LHS), i.e. $a_1 \downarrow$.
(7): $m_2 \uparrow$ reduces the marginal return of the mitigation (RHS). Thus this option also demands lower marginal costs (LHS), i.e. $m_1 \downarrow$ (→ indirect relevance for $\frac{da_1}{dm_2}$ via indirect effect).
Indirect effects (consider that (7) and (8) must be solved simultaneously)**:**

$m_1 \downarrow$ causes via (8) an increase in the weighting of the marginal returns of the mitigation and thus $a_1 \uparrow$.

Therefore the indirect effect counteracts the direct effect. Here $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ is proportional to the strength of the indirect effect. The direct effect is therefore greater when $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ is sufficiently small. In concrete terms, the following must apply:

$$ad - cb < 0 \Rightarrow \frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2} < \frac{\frac{\partial p(\cdot)}{\partial m_2}\frac{ds_1(a_1)}{da_1}\left(\frac{d^2 c_1(m_1)}{dm_1{}^2} + \frac{\partial^2 p(\cdot)}{\partial m_1{}^2} s_1(a_1)\right)}{s_1(a_1)\frac{\partial p(\cdot)}{\partial m_1}\frac{ds_1(a_1)}{da_1}}$$

Case (ii)

$\det H_{a_1 m_2} = 0 \Rightarrow |ad| = |cb|$; interpretation as in Case (i); $\left|\frac{\partial^2 p(\cdot)}{\partial m_1 \partial m_2}\right|$ in such a way that direct and indirect effects just neutralise each other.

Case (iii)

$\det H_{a_1 m_2} > 0 \Rightarrow |ad| < |cb| \rightarrow$ see above interpretation.

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