Chapter 17. Economics of Adaptation

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Executive Summary

In the presence of limited resources and a range of objectives, adaptation strategy choices involve trade-offs among multiple policy goals *(high confidence)*. The alternative policy goals include development and climate change mitigation. Economics offers valuable insights into these trade-offs and into the wider consequences of adaptation. It also helps to explain the differences between the potential of adaptation and its achievement as a function of costs, barriers, behavioral biases, and resources available. [17.2.7.1, 17.2.7.2, 17.3.1]

Economic thinking on adaptation has evolved from a focus on cost benefit analysis and identification of "best economic" adaptations to the development of multi-metric evaluations including the risk and uncertainty dimensions in order to provide support to decision makers (*high confidence*). Economic analysis is moving away from a unique emphasis on efficiency, market solutions, and benefit/cost analysis of adaptation to include consideration of non-monetary and non-market measures; risks; inequities; behavioral biases; barriers and limits and consideration of ancillary benefits and costs. One role of economics is to contribute information to decision makers on the benefits and costs, including a number of non-monetary items, and on the equity impacts of alternative actions. It does not provide a final ranking for policy makers. A narrow focus on quantifiable costs and benefits can bias decisions against the poor and against ecosystems and those in the future whose values can be excluded or are understated. Sufficiently-broad-based approaches, however, can help avoid such maladaptation. Indeed the evidence shows that maladaptation is a possibility if the evaluation approaches taken are not comprehensive enough in this sense. [17.2.3, 17.3.2]

The theoretical basis for economic evaluation of adaptation options is clear, and can be and has been applied to support decisions in practical contexts *(medium confidence)*. There is extensive experience of applying the concepts and methods underlying the economic framework in non-adaptation contexts, which is useful for designing climate adaptation policies. The limited empirical evidence available shows a number of cases where desirable adaptation strategies have been identified based on these economic tools. The findings show that adaptation is highly regional and context specific. Thus the results do not readily permit widespread generalizations about the nature of attractive adaptation actions. [17.2, 17.4.1, 17.4.2, 17.4.4].

Both private and public sectors have a role to play in the development and implementation of adaptation measures *(high confidence)*. Economic theory and empirical results show that a degree of adaptation will be autonomously carried out by private parties in response to climate change. However the private sector alone will often not provide the desirable level of adaptation with some types of actions not undertaken due to costs, incentives, nature of beneficiaries and resource requirements. This implies the public sector will need to play a strong role. There are also other reasons for public action such as overcoming barriers, developing technologies, representing current and future equity concerns and other items. [17.2.1, 17.3.1]

The theory and the evidence indicate that adaptation cannot generally overcome all climate change effects (*high confidence*). In addition to there being biophysical limits to adaptation, such as the inability to restore outdoor comfort under high temperatures, some adaptation options will simply be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs. Thus the desirability of adaptation options will vary with time and climate change realization. [17.2.2, 17.2.5]

Adaptation generally needs to be seen in the frame of the overall development path of the country, particularly for developing countries *(high confidence)*. Development and adaptation can be complementary or competitive. Also development can yield positive ancillary adaptation effects or co-benefits, provided it takes into account climate change in its design. Adaptation actions can provide significant co benefits such as alleviating poverty or enhancing development**.** Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as "mainstreaming". [17.2.7, 17.2.3.1, 17.2.3.2]

Not all adaptation actions are investment-based. Policy actions are also important tools for adaptation (*medium confidence*). These include direct R&D funding, environmental regulation, economic instruments, and education. Economic instruments have high potential as flexible tools because they directly and indirectly provide incentives for anticipating and reducing impacts and can have lower costs to the public budget. These instruments are currently not well explored in an adaptation context apart from risk financing instruments. Existing incentives will lead to a set of private adaptation actions. They include risk sharing and transfer mechanisms (insurance), loans, public private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including taxes, norms and regulations, and behavioral modification approaches. These instruments offer some useful possibilities for addressing climate change but they also have problems of effective implementation that need to be addressed. The problems can be particularly severe in developing countries. [17.4, 17.5]

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes and climate variability, but involve major design challenges so as to avoid providing disincentives, causing market failure and worsening equity situations (*medium confidence*). Mechanisms include insurance, reinsurance, micro insurance, and national, regional and global risk pools. The public sector often plays a key role as regulator, provider or insurer of last resort. Risk financing can directly promote adaptation through providing claim payments after an event, and allow for improved decisions under risk pre-event (strong evidence). It can also directly provide incentives for reducing risk, yet the evidence is weak and the presence of many counteracting factors often leads to disincentives, which is known as moral hazard.[17.5.1]

Global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit (limited evidence, *medium confidence*). The most recent global adaptation cost estimates suggest a range from $70 billion to $100 billion per year globally by 2050, but there is little confidence in these numbers. The evidence base is limited and there is strong evidence of important omissions and shortcomings in data and methods rendering these estimates highly preliminary (*high confidence*). Comparison of the global cost estimates with the current level of adaptation funding shows the projected global needs to be orders of magnitude greater than current investment levels particularly in developing countries**(***limited evidence***)**. [17.4.1, 17.4.2, 17.4.4].

Economics offers a range of techniques appropriate for conducting analysis in the face of uncertainties, and the choice of the most appropriate technique depends on the nature of the problem and the nature and level of uncertainty (*high confidence*).Uncertainty is unavoidable in analyses of adaptation to climate change because of lack of data, the efficacy of adaptation actions and because of uncertainties inherent in forecasting climate change. Approximate approaches are often necessary. There is a strong case for the use of economic decision-making under uncertainty, working with tools such as cost-benefit and related approaches that include a time dimensions (real options techniques), multi-metrics approaches and non-probabilistic methodologies. There are methodologies that are able to capture non-monetary effects and distributional impacts, and to reflect ethical considerations. [17.3.2.1, 17.3.2.2, 17.3.2.3]

Selected regional and sectoral studies suggest some core considerations and characteristics that should be included in the economic analyses of adaptation (*medium confidence*). These desirable characteristics include: a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternatives and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and nonmarket scope; and a strong focus on support of practical decision-making that incorporates consideration of sources of uncertainty. Few current studies manage to include all of these considerations [17.4.3].

17.1. Background

This chapter assesses the literature on the economics of climate change adaptation, building on the Fourth Assessment Report (AR4) and the increasing role that economic considerations are playing in adaptation decision-making and policy. AR4 provided a limited assessment of the costs and benefits of adaptation, based on narrow and fragmented sectoral and regional literature (Adger *et al*, 2007). Substantial advances have been made in the economics of climate change adaptation after AR4.

What are the Objectives of Adaptation?

The specific objectives involved in an adaptation effort can be diverse. One may try to cancel all impacts (negative and positive), maintaining the status quo. Alternatively one can try to cancel adverse impacts and capture positive opportunities, so that the welfare gain (or loss) is maximized (or minimized).

Part of the literature presents adaptation as a continuous, flexible process, based on learning and adjustments (IPCC SREX, Ch 8). Adaptation projects informed by this approach emphasize learning and experimenting, plus the value of using reversible and adjustable strategies (Berkhout *et al.*, 2006; Pelling *et al.*, 2007; Leary et al., 2008; McGray et al., 2007; Hallegatte, 2009; Hallegatte et al., 2011c).

Adaptation action and policy has also advanced since AR4, and the literature on the economics of adaptation has reflected this. This chapter builds on other chapters in this assessment, in particular Chapter 2, which sets the basis for decision-making, recognizing economics as a decision support tool for both public and private actors. The type of economic approach used depends on factors discussed in Chapter 2 among others, including the agent making the decision, the nature or type of decision, the information used to make the decision, who implements the decision, others affected by the outcomes and the values attached to those outcomes. While realizing the linkages between adaptation and mitigation, the starting point of this chapter is that adaptation is a given need.

This chapter assesses the scientific literature covering: the economic aspects of adaptation; decision making and economic context of adaptation, including economic barriers to adaptation decision making, and uncertainty; costing adaptation; and the economic and related instruments to provide incentives for adaptation.

17.2. Economic Aspects of Adaptation

When considering adaptation, economic studies give insight into issues regarding the roles of various actors in society, the character of adaptation strategies, the types of benefits and costs involved, the role of time and a number of other factors that we discuss in this section.

17.2.1. Public and Private Actors in Adaptation Implementation

Previous IPCC reports (TAR and FAR) indicate adaptation actions can be autonomous, planned or natural through ecological systems. Autonomous actions are mostly undertaken by private parties while planned can be undertaken by private or public actors. Natural adaptation is that occurring within the ecosystem in reaction to climate change but may be subject to human intervention (See discussion in chapter 14 section 14.1).

In terms of human actions there are important economic distinctions regarding the roles of private and public actors. Some adaptation actions create public goods that benefit many and in such cases the implementing party cannot typically capture all the gains. For example if an individual pays to protect a coastline or develop an improved irrigation system the gains generally go to many others. Classical economic theory (Samuelson, 1954) and experience plus observations regarding adaptation (Mendelsohn, 2000, Osberghaus et al 2010, Wing and Fisher-Vanden. 2013) indicate that such actions will not receive appropriate levels of private investment (creating a market failure). In turn, this calls for public action by elements of broader society (e.g. governments, NGOs, or international organizations). Other reasons for public provision or public regulation of certain adaptation measures that lead to less than a socially desirable level of adaptation are discussed in section 17.3.

17.2.2. Broad Categorization of Adaptation Strategies

There are many possible adaptation measures, as indicated in the TAR and FAR plus chapters 14 and 15. In economic terms these include a mixture of public and private actions taken in both domestic and international settings. A broad characterization of these and who might undertake them follows:

- Altered patterns of enterprise management, facility investment, enterprise choice or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g. dams and water management - mainly public)
- Technology development through research (e.g. development of crop varieties - private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles mainly public)
- Human capital enhancement (investment in education - private and public)
- Redesign or development of adaptation institutions (e.g. altered forms of insurance - private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g. altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations-mainly public)
- Changes in individual behavior (private with possible public incentives)
- Emergency response procedures and crisis management (mainly public)

Not all adaptation involves investment or is costly. Some adaptation measures involve modification of recurring expenditures as opposed to new investments (replacing depreciated equipment with more adapted items). Sometimes adaptation involves changes in behaviors and lifestyles (e.g. due to increased frequency of heat waves).

17.2.3. Broad Definition of Benefits and Costs

The consequences of adaptation decisions cannot be expressed comprehensively through standard economic accounting of costs and revenues. Adaptation decisions can also affect other items such as income distribution and poverty (Jacoby et al, 2011), the regional distribution of economic activity, including employment, non-market factors such as water quality, ecosystem function, and human health, and social organization and cultural practices.

Adaptation choices have broad ranging and complex impacts on such issues as:
- Macroeconomic performance (see, e.g., Fankhauser and Tol, 1995);
- Allocation of funds with a crowding out effect on other climate and non-climate investments with consequences for future economic growth (Hallegatte et al., 2007; Hallegatte and Dumas, 2008; Wang and McCarl, 2013)
- Welfare of current and future generations through resource availability and other non-monetary effects
- Risk distributions on all of the above due to routine variability plus uncertain estimates of the extent of climate change, adaptation benefits and costs.

A number of these items pose challenges for measurement and certainly for monetization. Generally this implies that any analysis be multi metric with part in monetary terms and other parts not, some in precise quantitative terms and others not (for more discussion see section 17.3). Also in view of this it is reasonable to conclude that an unbiased, comprehensive analysis would consist of a multi metric analysis encompassing cost benefit and other monetary items plus non-monetary measures. That analysis would support adaptation decision-making.

17.2.3.1. Ancillary Economic Effects of Adaptation Measures and Policies

In addition to creating an economy that is more resilient to the effects of climate change, adaptation strategies often have ancillary effects of substantial importance. These can be positive (co-benefits) or negative (co-costs). Ancillary effects also arise when actions primarily aimed at mitigation or non-climate related matters alter climate adaptation. Examples include:
- Sea walls that protect against sea level rise and at the same time protect against tsunamis. However they can also have co-costs causing damages to adjacent regions, fisheries and mangroves (Frihy, 2001);
- Crop varieties that are adapted to climate change have enhanced resistance to droughts and heat and so also raise productivity in non-climate change related droughts and temperature extreme (Birthal et al, 2011);
- Better building insulation which mitigates energy use and associated greenhouse gas emissions also improves adaptation by protecting against heat (Sartori and Hestnes, 2007);
- Public health measures that adapt to increases in insect-borne diseases also have health benefits not related to those diseases (Egbendewe-Mondzozo et al, 2011);
- More efficient use of water –adaptation to a drier world- will also yield benefits under current conditions of water scarcity. Development of improved desalination methods has the same merits (Khan et al, 2009);
- Locating infrastructure away from low-lying coastal areas provides adaption to sea level rise and will also protect against tsunamis;
- Reducing the need to use coal-fired power plants though energy conserving adaptation will also provide mitigation, improve air quality and reduce health impacts (Burtraw et al, 2003).

17.2.3.2. Economic Consideration of Ancillary Effects

Many studies argue that co-benefits should be factored into decision making (e.g. Viguie and Hallegatte (2012), Kubal et al. (2009), De Bruin et al. (2009), Brouwer and van Ek (2004), Ebi and Burton (2008), and Qin et al. (2008)). If a country has a fixed sum of money to allocate between two competing adaptation projects, and both strategies generate net positive ancillary effects, then the socially optimal allocation of adaptation investment will differ from the private optimum and will favor the activity with the larger direct plus ancillary effects.

17.2.4. Adaptation as a Dynamic Issue

Adaptation is not a static concern. Rather it evolves over time in response to a changing climate (Hallegatte, 2009). Adaptation is perhaps best handled via a long-term transitional, continuous, flexible process that involves learning and adjustment (IPCC SREX, Ch 8; Berkhout *et al.*, 2006; Pelling *et al.*, 2007; Leary et al., 2008; McGray et al., 2007; Hallegatte, 2009; Hallegatte et al., 2011c). Generally the literature indicates that optimal adaptation and the desirability of particular strategies will vary over time depending on climate forcing plus other factors like technology availability and its maturity (De Bruin et al, 2009b). In the next few decades, during which time projected temperatures do not vary substantially across socioeconomic/climate scenarios, adaptation is the main economic option for dealing with realized climate change. Risk is also an important aspect with the longer term being more uncertain that the near term. Risk-sensitive decisions often include the options of acting or of waiting (Linquiti and Vonortas, 2012). The issue of options is discussed further in Beltratti, Chichilnisky and Heal (1998) which covers uncertainty about future preferences through option values.

Dynamics also are involved with strategy persistence due to the decadal to century time scale implications of some adaptation strategies like construction of seawalls or discovery of drought resistant crop genes. The desirability of investments with upfront costs and persistent benefits increases when the benefits are long lasting or when climate change damages accumulate slowly (de Bruin 2011, Agrawala et al, 2011; Wang and McCarl, 2013). However, maladaptation effects rising over time are also possible as protecting now can expand investment in vulnerable areas and worsen future vulnerability (Hallegatte, 2011).

17.2.5. Practical Adaptation Strategy Attractiveness and Feasibility

Adaptation cannot reasonably overcome all climate change effects (Parry et al 2009). A number of factors will limit strategy adoption and preclude elimination of all climate change effects. A conceptual way of looking at this for a given adaptation endeavor is in Figure 17-1. The first outside circle represents the “adaptation needs”, i.e. the set of adaptation actions that would be required to avoid any negative effect (and capture all positive effects) from climate change. It can be reduced by climate change mitigation, i.e. by limiting the magnitude of climate change. The second circle represents the subset of adaptation actions that are possible considering technical and physical limits. Improving what can be done, for instance through research and development, can expand this circle. The area between the first and second circles is the area of “unavoidable impacts” that one cannot adapt to (for instance, it is impossible to restore outdoor comfort under high temperature). The third circle represents the subset of adaptation actions that are desirable considering limited resources and competing priorities: some adaptation actions will be technically possible, but undesirable because they are too expensive and there are better alternative ways of improving welfare (e.g., investing in health or education). This circle can be expanded through economic growth, which increases resources that can be dedicated to adaptation. Finally, the last circle represents what will be done, taking into account the fact that market failures or practical, political, or institutional constraints will make it impossible to implement some desirable actions (see chapter 15 and section 17.3). The area between the first and the last circles represents residual impacts (i.e. the impacts that will remain after adaptation, because adapting to them is impossible, too expensive, or impossible due to some barriers).

[INSERT FIGURE 17-1 HERE
Figure 17-1: The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.]

This discussion has consequences for timing of adaptation financing, given continuous changes in climate over time and uncertainties in the resulting impacts. Mathew et al. (2012) recommend the use of soft, short-term and reversible adaptation options with co-benefits for local governments. Giordano (2012) recommends the use of adaptive policies for modifying infrastructure, which can be robust across a wide range of plausible futures under climate change. Hochrainer and Mechler (2011) suggest that tools such as risk pooling may be more cost effective than risk reduction through engineering methods for low frequency but high impact hazards.

Financing adaptation programs is further discussed in the literature through the lens of distribution of costs. Stern, 2006) argues climate change is characterized by a “double inequity” with those countries that are most vulnerable having generally contributed least (on a per capita basis) to the climate change drivers (Panayotou *et al.*, 2002; Tol *et al.*, 2004; Mendelsohn *et al.*, 2006; Patz *et al.*, 2007; SEGCC, 2007; Srinivasan *et al.*, 2008; Füssel, 2010).

The distribution of responsibilities for financing adaptation has been subject of lively debate. Füssel et al. (2012) note that answering the following questions can inform the debate on such burden sharing issues:

- Who pays for adaptation and how much should they contribute into the adaptation fund and what criteria are appropriate in determining this?
- Who is eligible for receiving payments from the fund, and which criteria could be used for prioritising recipients and for allocating funds?
- Which adaptation measures are eligible for funding, and what are the conditions and modalities for payment?
- How and by whom are such decisions made?

As of now no definitive conclusions have been reached. Table 17-1 sets out different approaches to defining eligibility for receiving adaptation funds.

[INSERT TABLE 17-1 HERE
Table 17-1: Four definitions of eligible adaptation.]

17.2.6. Adaptation Benefits and Costs, Residual Damage and Projects

Adaptation benefits are the reduction in the damages plus any gains in climate related welfare that occur following an adaptation action. (U.S. National Academy of Sciences, 2010; World Bank 2010). Simplistically the cost of adaptation is the cost of any additional investment needed to adapt to or exploit future climate change (UNFCCC, 2007). But a full accounting needs to consider the resources spent to develop, implement and maintain the adaptation action along with accruing reduced damages or welfare increases involving monetary and non- monetary metrics.

Figure 17-2 provides a graphical representation of the link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). A fraction of climate change damage can be reduced at no cost (e.g. by changing sowing dates in the agricultural sector). With increasing adaptation cost, climate change costs can be reduced further. In some cases (left-hand panel), sufficiently high adaptation spending can take residual cost to zero. In other cases (right-hand panel), some residual cost of climate change is unavoidable. Economics tells that the optimal level of adaptation equalizes the marginal adaptation cost and the marginal adaptation benefit, given by the point on the adaptation curves where the slope is -45^{o}. If barriers and constraints (see section 17.3) impose a suboptimal situation, the marginal costs and benefits of adaptation are not equal, possibly because there is too much investment in adaptation, so that investing $1 in adaptation reduces climate change residual cost by less than $1, or because there is not enough investment in adaptation and investing $1 more in adaptation would reduce residual cost by more than $1 (the situation in the right-hand panel).

[INSERT FIGURE 17-2 HERE
Figure 17-2: Graphical representation of link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.]

Defining the costs and benefits of an “adaptation project” raises conceptual issues. Many actions have an influence on the impact of climate change without being adaptation projects per se (e.g., enhanced building norms). Many “adaptation projects” have consequences beyond a reduction in climate change impacts or an increase in welfare from exploiting opportunities (as discussed in the ancillary impacts section). Defining the adaptation component requires the definition of a baseline (What would be the impact of climate change in absence of the adaptation action? What alternative projects would be implemented in the absence of climate change?), and the definition of “additionality” – what amount of additional loss reduction or welfare gain happens because of the project. For instance, the building of new infrastructure may be marginally more costly because of adaptation to climate change but would still be undertaken without climate change and thus only a fraction of that cost and the resultant benefits would be labeled as occurring because of adaptation (See Dessai and Hulme 2007.)

In the climate change context, residual damages are those damages that remain after adaptation actions are taken. De Bruin et al (2009b) and Hof et al (2009) have examined the relationship between increasing adaptation effort and diminished residual damages.

17.2.7. A Broader Setting for Adaptation

Adaptation can be complementary to mitigation and to non-climate policies. An important concern is determining the balance between spending on adaptation versus that on other investments – mitigation and non-climate endeavors. Economics indicates the marginal social returns to all forms of expenditure should be the same, allowing for distributional impacts (which can be done by differentially weightings of benefits and costs to alternative income groups (Brent, 1996; Musgrave and Musgrave, 1973)).

17.2.7.1. Adaptation and Mitigation as Competitive or Complementary Investments

Adaptation and mitigation funding require coordination as they are competing uses for scarce resources (AR4 WGII chapter 18, Gawel et al, 2012). They also compete with consumption and non-climate investments. For example some adaptation strategies use land (a shift from crops to livestock) as does mitigation via afforestation or biofuels and all three would reduce ongoing crop production. Nevertheless considering both adaptation and mitigation widens the set of actions and lowers the total cost of climate change (de Bruin et al, 2009; Wang and McCarl, 2013; Koetse and Rietveld, 2012).

17.2.7.2. Adaptation and Development

There is a relationship between adaptation and socio-economic development, particularly in lower income countries (as extensively discussed in chapters 10, 13 and 20). In terms of complementarity between the two, studies show that both development and adaptation can be enhanced via: climate resilient road development (World Bank 2009); installation of agricultural investments that enhance income, heat tolerance and drought resilience (Butt et al. 2006, Ringer et al 2008); or improvements in public health infrastructure that increase capability to deal with climate-enhanced disease and other diseases (Samet 2010, Markandya and Chiabai 2009). Additionally development in general can increase adaptive capacity through enhancements in human and other capital (IPCC- SREX, 2012; Schelling 1992, 1997; Tol 2005). Finally adaptation efforts may reduce adaptation deficits regarding vulnerability to existing climate and enhance general development (Burton, 2004). Thus development goals can be generally consistent with adaptation goals, with one possibly being an ancillary effect of the other, although this is not always the case. For example, Hansone et al (2001) find that urbanization of flood-prone areas increases vulnerability and adaptation needs while Burby et al (2001) and Hallegatte (2012) indicate better protection may trigger additional development in at-risk areas and create increased vulnerability to extreme events.

17.3. Decision-Making and Economic Context for Adaptation

Adaptation will be carried out by multiple public and private actors who face a number of decision-making barriers that may limit adaptation. Chapter 16 and many papers (e.g., Fankhauser et al., 1999, Moser and Eckstrom 2010; Cimato and Mullan, 2010; Biesbroek et al 2011; Fankhauser & Soare, 2013) investigate these barriers. This section reviews them from an economic perspective, and then turns to the decision-making frameworks that can help implement adaptation actions in spite of these barriers.

17.3.1. Economic Barriers to Adaptation Decision-Making

17.3.1.1. Transaction Costs, Information, and Adjustment Costs

Transaction costs include the costs of accessing markets and information, along with reaching an agreement and enforcement costs (Coase, 1937 and 1960; Williamson, 1979). Because of transaction costs, a beneficial adaptation action may be undesirable. Two specific types of transaction costs are those relating to information and those relating to adjustment. Information acquisition costs can represent a significant obstacle, for instance when climate and weather data are costly or difficult to access (e.g., Cimato and Mullan 2010; Scott et al 2011; Ford et al. 2011). Since information is a public good, private actors tend to underprovide it and there is a role for government and public authorities to support its production and dissemination (e.g., through research funding, observation networks, or information distribution systems) (Fankhauser et al., 1999; Mendelsohn 2000; Trenberth 2008). Adjustment costs represent another barrier, especially in the presence of uncertainty and learning, and when long-lived capital is concerned. Fankhauser et al (1999) discuss adjustment costs as a barrier to early capital replacement to adapt to a different climate. Kelly and Kolstad (2005) define adjustment costs as the cost incurred while learning about new climate conditions. Using these different definitions, these analyses suggest that adjustment costs can represent a significant share of adaptation costs.

17.3.1.2. Market Failures and Missing Markets

Adaptation may also face market failures such as externalities, information asymmetry, and moral hazards (see 17.2.1; Osberghaus et al 2010). As a consequence, some socially desirable actions may not be privately profitable. For example, flood mitigation measures may not be implemented in spite of their benefits, when flood risks are partly assumed by insurance or post-disaster support, transferring risk to the community (a case of moral hazard, Burby et al., 1991; Laffont 1995). There are also externalities, since adaptation actions by one household, firm, or even country may create higher damages for others. This is the case with trans-boundary waters, when increased irrigation in one country creates water scarcity downstream (Goulden et al 2009). Trans-sector effects can also take place, for instance when adaptation in one sector creates needs in another sector (e.g., the impact on transportation of agriculture adaptation, see Attavanich et al 2013). Incentives for private adaptation actions may also be lacking for public goods and common resources without property rights (e.g., biodiversity and natural areas, tradition and culture). And adaptation may exhibit increasing returns or large fixed costs, leading to insufficient adaptation investments (e.g., Eisenack 2013). In such contexts, public norms and standards, direct public investment, tax measures, or national or international institutions for adaptation coordination are needed to avoid maladaptation.

17.3.1.3. Behavioral Obstacles to Adaptation

Economic agents adapt continuously to climate conditions, though not always using the available information, especially long-term projections of consequences (Camerer and Kunreuther, 1989, Thaler, 1999, Michel-Kerjan, 2008). Individuals often defer choosing between ambiguous choices (Tversky and Shafir 1992; Trope and Lieberman, 2003) and make decisions that are time inconsistent (e.g., they attribute a lower weight to the long term through “hyperbolic discounting”, see Ainslie 1975). They also systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003). Also, individuals value profits and losses differently (Tversky and Kahnman 1974). Behavioral issues may lead to suboptimal adaptation decisions, as illustrated with case studies in Germany and Zimbabwe in Grothmann and Patt (2005). Particularly important is the fact that the provision of climate information needs to account for cognitive failures (Suarez and Patt 2004; Osberghaus et al 2010b). Individual behavioral barriers extend to cultural factors and social norms, which can support or impair adaptation as illustrated by Nielsen and Reenberg (2010) in Burkina Faso.

17.3.1.4. Ethics and Distributional Issues

A difficulty in allocating adaptation resources noted in 17.2.3 is the limitation of indicators based on costs and benefits (Adger et al, 2005; Füssel, 2010). Outcomes are often measured using such methods but their limits are well known, (e.g., CMEPSP, 2009; OECD, 2009, Heal 2012) and include the failure to take into account resource depletion, environmental change, and distributional issues.

Distributional issues may justify public intervention based on ethics and values. Climate change impacts vary greatly by social group, and many have suggested that the poor are particularly vulnerable (e.g., Stern, 2006; Füssel et al. 2012). Some individuals, firms, communities and even countries may be unable to afford adaptation, even if it is in their own interest. Also, individuals with different world views or preferences (e.g., regarding risk aversion, see Adger et al 2009) may ask for different adaptation measures and have different views of what is an acceptable level of residual risk (Peters and Slovic 1996). Consideration of justice and fairness will play a role in adaptation option design (Adger et al 2006; Pelling and Dill, 2009; O'Brien et al., 2009; Dalby 2009; Brauch, 2009a, 2009b; O'Brien et al., 2010b). The implementation of adaptation options may thus require taking into account the political economy of reforms and the need to compensate losers (World Bank 2012).

The traditional economic approach suggests choosing the most cost-effective projects and then resorting to financial transfers to satisfy equity objectives (Atkinson and Stiglitz, 1976; Brown and Heal 1979). However this embodies strong assumptions including the ability to realize perfect and costless financial transfers. In more realistic situations the choice is not so clear cut. In practical terms transfers are difficult to organize and may not be politically acceptable (Kanbur 2010). In these cases, adaptation decision-making needs to account for both the net benefits and the impacts on equity (Aakre and Rübbelke 2010).

17.3.1.5 Coordination, Government Failures, and Political Economy

One of the main roles of governments and local authorities is to remove barriers: realigning the incentives of individuals with the goals of society, providing the public goods needed for adaptation, or helping with behavioral and cognitive biases. But governments and local authorities face their own barriers, often referred to as government or regulatory failures (Krueger 1990). First, government and local authority decision makers, as individuals, face their own barriers, such a cognitive and behavioral biases (Podsakoff et al, 1990). Public decision-makers are also confronted with moral hazard, for instance when subnational entities are provided support from the government in case of disaster (Michel-Kerjan 2008). Second, governments may have access to insufficient resources or limited adaptation capacity, especially in poorer countries and where governments have limited access to capital markets and are unable to fund projects, even when they are cost-efficient (e.g., Smit and Wandel 2006; Brooks et al 2005; World Bank 2012). There can also be coordination failures within the government, since many adaptation options require multi-ministry actions (e.g., the reduction of flood risks may require some prevention measure implemented by the environmental ministry and an insurance scheme regulated by the ministry of finance, World Bank 2013).

Other government failures can arise. Frequently government action is driven by narrow interest groups and is not in the public interest (James 2000, Levine and Forrence 1990). Multi-stakeholders approaches have been shown to help address these problems, a relevant example for this context being coral reef management in Tobago (Adger et al 2005).

17.3.1.6. Uncertainty

Decisions about adaptation have to be made in the face of uncertainty on items ranging from demography and technology to economic futures. Climate change adds additional sources of uncertainty, including uncertainty about the extent and patterns of future climate change (see the AR5 WGI report), which is dependent on uncertain socio-economic development pathways and climate policies (see the AR5 WGIII report), and uncertainty about the reaction and adaptation of ecosystems (see Chapters 3 to 13).

Patt and Schröter (2008) show in a case study in Mozambique that major uncertainties are a strong barrier to successful adaptation. Uncertainty coupled with the long lifespan of a number of options can lead to "maladaptation," i.e. an adaptation action that leads to increased vulnerability. An "*avoidable*" maladaptation arises from a poor *ex ante choice*, where available information is not used properly. An "*unavoidable*" *ex post* maladaptation can result from entirely appropriate decisions based on the information that was the best available *at the time of decision-making*, but subsequently proves to have been wrong. An example of the latter is a precautionary restriction prohibiting new construction in areas potentially at risk of sea level rise. Applying such a precautionary approach makes sense when (i) decisions are at least partly irreversible (e.g., building in flood-prone areas cannot easily be "un-built") and (ii) the cost of a worst-case scenario is very high. Such a precautionary measure can make economic sense *ex ante*, even if sea level rise eventually remains in the lower range of possible outcomes, making the construction restriction unnecessary.

17.3.2. Economic Decision making with Uncertainty

Decision making under uncertainty is a central question for climate change policy and is discussed in many chapters of the AR5, and especially in chapter 2 of WGII and chapters 2 and 3 of WGIII. This section focuses on the economic approaches to decision-making under uncertainty, including decision-making techniques, valuation tools, and multi-metric decision-making.

17.3.2.1. Cost-Benefit Analysis and Related Methods

There are different tools for decision-making that can be applied in different contexts and with different information. Cost-benefit analysis under uncertainty applied to adaptation uses subjective probabilities for different climate futures (e.g., Tebaldi et al., 2005; New and Hulme, 2006; see also chapter 2). The "best" project is the one that maximizes the expected net present value of costs and benefits. Risk aversion can be taken into account through (nonlinear) welfare functions or the explicit introduction of a risk premium.

When conducting cost-benefit analyses under uncertainty, an important question is the timing of action, i.e. the possibility of delaying a decision until more information is available (e.g., Fankhauser and Soare, 2013). Real option techniques are an extension of cost-benefit analysis to capture this possibility and balance the costs and benefits of delaying a decision (Henry 1974, Arrow and Fisher 1974). The benefits depend on how much learning can take place over time. A key issue concerns irreversible actions, such as the destruction of a unique environment (Heal and Kristrom 2003).

Application of cost-benefit or real option analysis requires evaluations in monetary terms. For market impacts, prices may need to be corrected for policies, monopoly power or other external factors distorting market prices (Squire and van der Tak, 1975). But a cost-benefit analysis also often requires the valuation of non-market costs and benefits. This is the case for impacts on public health, cultural heritage, environmental quality and ecosystems, and distributional impacts. Valuation of non-market impact is difficult because of values and preferences heterogeneity, and subject to controversies; e.g., on the value to attribute to avoided death, see Viscusi and Aldy (2003).

There has been progress in valuation of ecosystem services, as elaborated in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB 2010) and Bateman et al (2011). Two main categories of approaches have been developed: revealed and stated preference methods. The latter is based on what people say about their preferences, while the former uses their actual decisions (e.g. how much they pay for a house) and are often considered more accurate. Other approaches include avoided or replacement cost, i.e. measuring the cost of providing the ecosystem service artificially. When local information is not available, value transfer techniques can be applied moving information from other locations. For example Brander et al (2012) applies value transfer to climate change impacts on wetlands but caution is required in making such transfers (Navrud and Ready 2007, U.S. National Research Council 2005).

Theoretically, cost-benefit approaches can account for distributional impacts, for instance through attribution of a higher weight to the poorest (Harberger, 1984). Results are however highly dependent on preferences that can be extremely heterogeneous and difficult to measure (Barsky et al 1997). As discussed in detail in chapter 2, valuation and decision-making cannot be separated from the institutional and social contexts (e.g., what is considered as a right). Yet, overall, as concluded by the IPCC-SREX, the applicability of rigorous CBAs for evaluations of adaptation to climate variability and change may be limited (Handmer et al., 2012).

17.3.2.2. Multi-Metric Decision-Making for Adaptation

Multi-metric decision-making provides a broader framework, which also permits balancing among multiple, potentially competing objectives *(*Keeney and Raiffa, (1993). This branch of decision analysis is also known as multi-criterion analysis. Such an approach is helpful when decision-makers have difficulty in trading off different objectives (Martinez-Alier et al 1998). Using multiple criteria, decision-makers can include a full range of social, environmental, technical, and economic criteria—mainly by quantifying and displaying trade-offs. Multi-criterion analyses have been applied to adaptation issues including urban flood risk (Grafakos 2011; Kubal et al. 2009; Viguie and Hallegatte 2012), agricultural vulnerability (Julius and Scheraga 2000) and choice of adaptation options in the Netherlands (De Bruin et al. 2009; Brouwer and van Ek 2004), Canada (Qin et al. 2008) and Africa (Smith and Lenhart 1996). The UNFCCC developed guidelines for the adaptation assessment process in developing countries in which it suggests the use of multi-criteria analysis (UNFCCC 2002). As an illustration, Figure 17-3 shows a multi-criteria analysis of three urban policies in the Paris agglomeration, using five policy objectives and success indicators (climate change mitigation, adaptation and risk management, natural area and biodiversity protection, housing affordability, and policy neutrality).

[INSERT FIGURE 17-3 HERE
Figure 17-3: Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using 5 different metrics representing 5 policy objectives. Axes orientation is such that directions towards the exterior of the radar plot represent positive outcomes. Source: Viguié and Hallegatte, 2012.]

17.3.2.3. Non-Probabilistic Methodologies

Cost-benefit analysis and related methods require probabilities for each climate scenario. But in most cases, it may be impossible to define (or to agree upon) probabilities for alternative outcomes, or even to identify the set of possible futures (including highly improbable events) (Gilboa 2010, Henry and Henry, 2002, Millner et al 2010 and Kunreuther et al 2012). This is especially true for low-probability, high-impact cases or poorly-understood risks (Weitzman 2009, Kunreuther et al. 2012). In such context, various approaches have been proposed (see reviews in Ranger et al, 2010; Hallegatte et al 2012; and chapter 2).

Scenario-based analyses study different policies in different scenarios that try and cover the uncertainty space for key parameters (Schwartz 1996). This is the approach followed by many climate change impact and adaptation studies when using several SRES scenarios (Carter et al., 2001; Carter et al., 2007, Hallegatte et al, 2011). Then, various methodologies or criteria can be used to make a decision.

The *maxi-min* criterion suggests choosing the decision with the best worst-case outcome and the *mini-max regret* criterion (Savage, 1951) suggests choosing the decision with the smallest deviation from optimality in any state of the world. Proposals for ‘no regrets’ adaptation decisions (Callaway and Hellmuth, 2007; Heltberg et al., 2009) employ such criteria. Hybrid criteria balance between optimal and worst case performance (Hurwicz, 1951; Aaheim and Bretteville, 2001; Froyn, 2005).

Another criterion is based on “robustness”, a criterion that seeks decisions that will perform well over a wide range of plausible climate futures, socio-economic trends, and other factors (Lempert and Schlesinger, 2000; Lempert et al 2006; Lempert and Collins 2007; Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Instead of starting from a few scenarios, these methods start with an option or a project and test it under a large number of scenarios to identify its vulnerabilities to uncertain parameters. Small adjustment or large changes in options or projects can then be identified to minimize these vulnerabilities. Example implementations include InfoGap, which has been used to inform adaptation decisions in water management (Ben-Haim, 2001; Korteling et al., 2013); RDM (robust decision making), which has been used for water management and flood risk management planning (Lempert et al., 2003; Lempert and Groves, 2010; Lempert and Kalra, 2011; Matrosov et al., 2013); and robust control optimization (Hansen and Sargent, 2008).

Figure 17-4 illustrates the application of robust decision-making on flood risks in Ho Chi Minh City (Lempert et al 2013). The analysis examined different risk management portfolios (including for instance raising homes and retreat). Each portfolio was simulated in 1,000 scenarios, covering socio-economic and climate uncertainty. The RDM analysis found that the current plan is robust to a wide range of possible future population and economic trends. But it would keep risk below current levels only if rainfall intensities increase by no more than 5 percent and if the Saigon River rises less than 45 centimeters. Additional measures were found that made the situation robust for increases in rainfall intensity of up to 35 percent and increases in the level of the Saigon River of up to 100 centimeters.

[INSERT FIGURE 17-4 HERE
Figure 17-4: Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change. Source: Lempert et al., 2013.]

17.4. Costing Adaptation

Interest in estimating the costs of adaptation has grown as the need for action has become clearer. The literature focuses on two levels of costing: global scale estimates, largely to assess the overall need for adaptation finance funds; and regional and local-scale estimates, often limited to a particular vulnerable economic sector, which may be applied to inform budgeting or to support adaptation decision-making, or to allocate scarce resources among the best prospects for effective adaptation. The methods for these two types of studies vary considerably, but for the important methodological considerations for costing adaptation are similar for both types.

17.4.1. Methodological Considerations

Data Quality and Quantity: There is very little discussion of data gaps related to assessing the benefits of adaptation, but poor or sparse data obviously limit the accuracy of these estimates. Callaway (2004) suggests that a major challenge is the low quality and limited nature of data, especially in many developing countries, and notes many transactions are not reported because they occur in informal economies and social networks. In a more general setting Hughes et al (2010) note that historical weather data is not typically sufficiently detailed while others note sparse data on costs of adaptation actions. For example, Bjarnadottie et al. (2011) note incomplete and contradictory data on house retrofit costs for hurricane protection . Also there are simply missing non-market data on such items as the value of ecosystem services (Agrawala and Fankhauser 2008), particularly as affected by climate and possible adaptation.

Costs and Benefits are Location-Specific: Calculating localized impacts requires detailed geographical knowledge of climate change impacts, but these are a major source of uncertainty in climate models (see Refsgaard et al. 2013). Global estimates of adaptation cost are generally not grounded in local-scale physical attributes important for adaptation, which in part explains why local and regional-scale adaptation cost estimates are not consistent with global estimates (Agrawala and Fankhauser 2008). Compared with developed countries, there is also a limited understanding of the potential market sector impacts of climate change in developing countries.

Costs and Benefits Depend on Socio-Economics: It is sometimes assumed that climate will change but society will not (Pielke, 2007; Hallegatte et al 2011; Mechler and Bouwer, 2013). Future development paths affect climate change impact estimates, and can alter estimates from positive to negative impacts or vice versa. Some studies show higher growth rates raise hurricane vulnerability (Bjarnadottir, 2011). On the other hand, higher incomes allow the funding of risk-reducing policies.

Discount Rates Matter: Because adaptation costs and consequences occur over time, discount rates are a core question. Opinions vary sharply on this question (Baum, 2009, Heal 2009). Hof et al (2010) notes that a low discount rate is needed for distant future climate change to matter. A low discount rate is the primary reason for the relatively high estimates of climate damage in the Stern Review (Stern 2006).

For climate adaptation projects, the social or consumption discount rate is the relevant one (Heal 2009). The rates used fall between 0.1 and 2.5%, although without good arguments for specific values (see Heal 2009). Nordhaus (2007) chooses a value of 1.5% while Stern uses a much lower value of 0.1%. Nordhaus emphasizes consistency with the rate of return on investment as a driving rationale while Stern points to ethical issues. Allowing environmental services to enter consumption can change the social discount rate substantially and generate a low or even negative social discount rate (Heal, 2009; Guesnerie, 2004; and Sterner and Persson, 2007). The UK Treasury now mandates the use of declining discount rates for long-term projects, as suggested by behavioral studies and by theoretical analysis (Arrow et al. 2012).

17.4.2. Review of Existing Global Estimates: Gaps and Limitations

There has been a limited number of global and regional adaptation cost assessments over the last few years (World Bank, 2006; Stern, 2006, Oxfam, 2007; UNDP, 2007, UNFCCC, 2007; 2008; World Bank, 2010a). These estimates exhibit a large range and have been completed mostly for developing countries. The most recent and most comprehensive to date global adaptation costs range from $70 to more than $100 billion annually by 2050 (World Bank, 2010a, see Table 17-2).

[INSERT TABLE 17-2 HERE
Table 17-2: Estimates of global costs of adaptation.]

IPCC (2011) considers confidence in these numbers to be *low* because the estimates are derived from only three relatively independent lines of evidence. The World Bank (2006) estimates the cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA), as does the Stern Review (2006), Oxfam (2007) and UNDP (2007). UNFCCC (2007) calculated existing and planned investment and financial flows (I&FF), and then estimated the additional investment required for adaptation as a premium on existing and planned investments. The World Bank (2010) followed the UNFCCC (2007) methodology of estimating the premium climate change imposes on a baseline of existing and planned investment, but included more extensive modeling as opposed to developing unit cost estimates, constructed marginal cost curves and climate stressor-response functions for adaptation actions, and included maintenance and coastal port upgrading costs.

Given their common approaches these estimates are interlinked, which explains the seeming convergence of their estimates in later years, as discussed by Parry et al (2009). However there are important differences in terms of sectoral estimates, as Figure 17-5 shows in comparing the UNFCCC (2007) and World Bank (2010a) studies. Extreme events, a potential source of large adaptation costs, are not properly covered, and these studies take into account a limited set of adaptation options. In addition, the World Bank (2010a) estimates report higher ranges of estimates, reflecting additional effort to account for uncertainty Parry et al. (2009) consider the UNFCCC (2007) estimates a significant underestimation by at least a factor of two to three plus omitted costs in ecosystem services, energy, manufacturing, retailing and tourism. Thus the numbers have to be treated with caution. There are a number of gaps, challenges and omissions associated with those global estimates that merit further discussion.

[INSERT FIGURE 17-5 HERE
Figure 17-5: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, points indicate point estimates.]

The practical challenges of conducting global adaptation cost studies are apparent in the literature (as assessed in IPCC 2011; World Bank 2010a; Parry et al. 2009). The broad scope of these studies limits the analysis to few climate scenarios, and while the scenarios might be strategically chosen it is difficult to fully represent the range of future adaptation costs across all sectors. The broad scope also limits comprehensive consideration of adaptation options, non-market and co-benefits, equity issues, and adaptation decision-making (such limitations also apply to local and regional scale studies - see Section 17.4.3). The global studies, designed to reflect the best available methods and data for the purpose of estimating the magnitude of the global economic adaptation challenge, achieve this limited goal but must be interpreted in light of these important limitations and uncertainties.

17.4.3. Consistency between Localized and Global Analyses

Adaptation costs and benefits are derived to guide specific investment decisions, generally at national and local levels, or to derive a "price tag" for overall funding needs for adaptation (generally at a global level). Given these different purposes it is difficult to compare "local", i.e, national and sectoral, with global numbers. The quantity/quality of local studies also varies by sector with more treatment of adaptation in coastal zones and agriculture (Agrawala and Fankhauser, 2008 – see Table 17-3). Less is known and many gaps remain for sectors such as water resources, energy, ecosystems, infrastructure, tourism and public health. Also assessments have predominantly been conducted in a developed country context (see Table 17-1 for examples of costs and benefits assessment).

[INSERT TABLE 17-3 HERE
Table 17-3: Coverage of adaptation costs and benefits.]

However, as Fankhauser (2010) notes, with the sole exception of coastal protection costs, adaptation costs have shown little convergence locally or in terms of sectoral to global costs. The World Bank (2010a) study uniquely takes a two-track approach doing parallel national (7 cases) and global adaptation estimates. For a number of country studies (Bangladesh, Samoa and Vietnam) a cross-country comparison of local and global adaptation costs was made, with the costs in terms of GDP found to be in reasonable agreement. Costs for strengthening infrastructure against windstorms, precipitation and flooding were about 10-20% higher compared to disaggregated global estimates, largely owing to the ability of country-level studies to consider at least some socially contingent impacts (World Bank 2010b, 2010c, 2010d). Further, there is evidence of under investment in adaptation (UNDP, 2007) with global estimates of the need for adaptation funds variously estimated in the range of $70-100 billion annually (World Bank 2010a), but with actual expenditures in 2011 estimated at $244 million (Elbehri et al, 2011), and in 2012 estimated at $395 million (Schalatek et al., 2012).

17.4.4. Selected Studies on Sectors or Regions

This section focuses on studies that illustrate current practice in estimating adaptation economics, with a particular focus on support of adaptation decision-making through economic analysis. Within that class of work, there are two broad categories of economic analyses of adaptation at the sectoral level: econometric and simulation approaches.

Econometric studies generally examine the nature of observed adaptations or the estimation of climate change effects to which farmers have adapted. Such studies rely on observed cross-sectional, time series, or panel data. Examples include those where one implicitly assumes adaptation has occurred linking temperature and precipitation to land values and crop yields or land values (e.g., Mendelsohn et al., 1994; Schlenker et al., 2006) or those identifying adaptations in terms of altered decisions (e.g. Seo and Mendelsohn, 2008a and 2008c) look at enterprise choice - while Mu et al., 2013 look at stocking rate adjustments). Such approaches can also be used to estimate the marginal effect of adaptation, provided that "without adaptation" estimates can be developed (Mendelsohn and Dinar, 2003).

The simulation approach, by contrast, traces costs and benefits of adaptation strategies through mechanisms of interest, typically through a series of climate-biophysical-behavioral response–economic components. Within simulation modeling there are two main threads in the behavioral response/economic component of the simulation. The first involves rational actors who consider the benefit and cost consequences of their choices and pursue economically efficient adaptation outcomes, and the second involves a decision-rule or reference based characterization of the response of actors to climate stressors (Dinar and Mendelsohn, 2011; Schlenker et al, 2006). As noted below, in many sectors the current practice begins with the simpler decision-rule based approach, and may progress to consider benefits and costs, and then perhaps to consider other factors, such as equity and nonmarket values.

The key advantages of an econometric approach are reliance on real-world data, the use of "natural experiments" in some cases, and an ability to reflect the joint costs and benefits of multiple adaptation strategies to the extent they are employed together in real world (Mendelsohn and Neumann, 1999; Dinar and Mendelsohn, 2011). The econometric approach does not require the analyst to simulate all adaptation mechanisms, only to establish that there is a robust relationship is between a climate stressor and the outcome of interest. The data required to implement the approach are limited, so the approach can be applied broadly. The key disadvantages of the econometric approach are an inability to trace transmission mechanisms of specific adaptation measures or to isolate the marginal effect of these strategies or measures; the inability to transfer estimates out of context (e.g., an African study does not apply to Asia, where the climate, adaptation, and social context all differ and affect the marginal costs and benefits of adaptation measures); and that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al., 2005).

Simulation modeling can be demanding – a key disadvantage – as it requires extensive data inputs and careful calibration. Where data and models are available, however, the simulation modeling method works well. For example, an agricultural adaptation modeling system can estimate such factors as the incremental change in crop output and water supply in response to changes in climatic conditions and agricultural and water resource management techniques. A further advantage of the simulation approach is that it provides an opportunity for stakeholder involvement at several stages of the analytic process: designing scope, adjusting parameters, selecting inputs, calibrating results, and incorporating adaptation measures of specific local interest (Dinar and Mendelsohn, 2011).

There is a wide range of studies available attempting an economic evaluation of adaptation options. From these, several desirable characteristics can be identified:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes(for example, a range of individual climate model forecasts and greenhouse gas emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result from the analysis are robust across a range of future outcomes (Agrawala *et al.*,2011; Lempert and Kalra 2009, also see Chapter 2).
- Representation of a wide variety of alternative adaptation responses (for example, in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, single adaptation response with variation in dimension may be useful (for example, varying the height of a levee or the capacity of a dam spillway) (World Bank 2010, Fankhauser 2010, Fankhauser et al. 1999).
- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, nonmarket, and socially contingent implications (Watkiss, 2011); one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (World Bank, 2010a).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision-making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al. 2006, also see Chapter 2).

Table 17-4 highlights studies that illustrate some of these characteristics. The studies include both simulation studies of the economic implications of adaptation options, and econometric ones which examine choices that producers make to adapt. These studies generally fall in the category of positive economics, where economic tools and analysis are used to examine the implications of alternative choices without imposing values of the author (see Friedman (1953)). A few studies incorporate a normative perspective, either explicitly or implicitly, reflecting value judgments of authors or study participants.

[INSERT TABLE 17-4 HERE
Table 17-4: Studies illustrating economic evaluation of adaptation options.]

17.5. Economic and Related Instruments to Provide Incentives

Through regulations, subsidies and direct intervention, there are many opportunities for policy makers to encourage autonomous adaptation. However, these efforts need to be designed so as to yield efficient, cost effective responses while avoiding perverse results. A basic issue of designing efficient policies is to understand that they affect the behavior of those who have the most to gain. For this and other reasons, economists tend to favor policies based on voluntary actions influenced by incentives, either positive or negative, over mandates or uniform policies. Examples of these include insurance markets, water markets and various Payments for Environmental Services (PES), as we discuss below. A second consideration in policy design is cost effectiveness, i.e. the extent to which governments make the best use of their resources. The measurement of the net effect of a policy is challenging because it is difficult to anticipate what would have occurred without the policy.

Finally, policies must be carefully designed to avoid perverse outcomes that run counter to the policy maker's objectives. A classic example is found in policies that encourage adoption of water-saving technology. Pfeiffer and Lin (2010) review cases where subsidizing irrigation water conservation leads farmers to increase total water use by increasing the acreage under irrigation. This is an example of what is often called the rebound effect (Roy, 2000) whereby increases in efficiency of resource use result in more being demanded.

With the exception of insurance and trade related instruments there is relatively little literature on the use of economic instruments for adaptation (see chapter 10). One reason is that, apart from insurance, few adaptation policies work directly via economic incentives and markets. The potential of economic instruments in an adaptation context is, however, widely recognized. In line with Agrawala and Fankhauser (2008) we distinguish, among others the following incentive-providing instruments relevant for key sectors: (i) Insurance schemes (all sectors; extreme events), (ii) Price signals / markets (water; ecosystems (iv) Regulatory measures and incentives (building standards; zone planning); and (v) Research and development incentives (agriculture, health).

17.5.1. Risk Sharing and Risk Transfer, Including Insurance

Insurance-related formal and informal mechanisms can directly lead to adaptation and provide incentives or disincentives. Informal mechanisms include reliance on national or international aid or remittances, and while such mechanisms are common, they tend to break down for large, covariate events (Cohen and Sebstad, 2005). Another informal mechanism is the inclusion of climate change risk under corporate disclosure regulations (National Round Table on the Environment and the Economy, 2012). Formal mechanisms include insurance, micro-insurance, reinsurance, and risk pooling arrangements. Insurance typically involves ongoing premium payments in exchange for coverage and post event claim payments. In contrast to indemnity-based insurance, index-based insurance insures the event (as e.g. measured by lack of rainfall) not the loss, and is a possibility for providing a safety net without moral hazard, yet suffers from basis risk, the lack of correlation of loss to event (Hochrainer et al. 2009; Collier et al. 2009) (see also 10.7 for a supply-side-focussed perspective on insurance). Markets differ substantially according to how liability and responsibility is distributed (Botzen et al., 2009; Aakre et al., 2009), and in many instances governments play a key role as regulators, insurers, or reinsurers (Linnerooth-Bayer et al., 2005). Insurance penetration in developed countries is considerable, whereas it is low in many developing regions. In the period 1980-2004 about 30% of losses were insured in high-income countries; but only about 1% in low-income countries (Linnerooth-Bayer et al., 2011). Developing countries are beginning to pool risks and transfer portions to international reinsurance markets. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) set the precedent by pooling risks basin wide, thus reducing insurance premiums against hurricane and earthquake risks (World Bank, 2007). Similar schemes are under development planning in Europe, Africa and the Pacific (Linerooth-Bayer et al. 2011).

Insurance-related instruments may promote adaptation directly and indirectly: i) instruments provide claim payments after an event, and thus reduce follow-on risk and consequences; (ii) they alleviate certain pre-event risks and allow for improved decisions (Skees et al., 2008; Hess and Syroka, 2005; Hoppe and Gurenko, 2006). As one interesting example, using crop micro insurance linked to loans, farmers exposed to severe drought in Malawi were able to grow higher-yield, yet higher-risk crops, which allowed them to increase incomes (Linnerooth-Bayer and Mechler, 2011).

The indirect effects occur via the provision of incentives and disincentives. Premiums for risk coverage can provide an incentive to reduce the premium by reducing the risk. In practice, the incentive effect is generally weak. Kunreuther et al. (2009) found that insurance decisions are not based solely on costs and premiums, but also desires to reduce anxiety, comply with mortgage requirements, and satisfy social norms. Further, purchasing insurance may reduce adaptation with insured agents reducing their risk-minimizing efforts after taking out coverage. This is termed moral hazard and has been found to be rational (Kunreuther, 1998). Moral hazard can be reduced though the use of index-based insurance, although this has the drawback of operating from a high base risk (Hochrainer et al. 2009: Collier et al., 2009). Another difficulty arises when local or state regulations undermine incentives to decrease risk (for instance, by not allowing insurance rates to be fully risk adjusted). Some analysts suggest the removal of existing regulations that distort market signals in order to re-align incentives, yet this is likely to be ineffective given that the incentive effect is not considered very strong and often premiums are not fully risk-based (Michel-Kerjanand Kunreuther, 2011). Also, Rao and Hess (2009) argue there is the possibility that some current insurance schemes may increase maladaptation. Under-insurance can also arise when agents expect that the public sector will provide disaster assistance. Some refer to this as the Samaritan's dilemma (Gibson et al., 2005; Raschky et al., 2013).

17.5.2. Payments for Environmental Services

Payment for Environmental services (PES) pay landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change adaptation and mitigation. There are ample cases of mitigation–focused PES schemes (e.g. Wunder and Borner (2011), Pagiola (2008), Wunder and Albán (2008)), and more recently emerging evidence of the use of PES in adaptation which are of pilot nature and location-specific however. (Butzengeiger_Geyer et al., 2011; van de Sand, 2012; Schultz, 2012). Potentially well designed PES schemes offer a framework for adaptation and there is a view among development agencies that with more experience and guidance on implementation PES might well contribute to adaptation as one of a multitude of feasible measures (e.g.. taxes, charges, subsidies, loans). Chishakwe *et al* (2012) draws comparisons and find synergies between PES community based natural resources management approaches in Southern Africa and community-based adaptation.

17.5.3. Improved Resource Pricing and Water Markets

Studies of water sector adaptation often begin by citing the implications of future water shortages and the potential for conflict. Techniques frequently cited for resolving these conflicts include the establishment of water markets or water pricing schemes (e.g., Alavian et al. 2009; Vorosmarty et al. 2000, Adler, 2008), which is in itself, however, also often associated with conflict (Miller et al., 1997). Traditionally water markets facilitate transfer from lower to higher-valued uses (Olmstead, 2010) but pricing rules can also function through urban fees and real estate taxes (as they do for water supply and urban storm water regulation in many countries). A few studies make the case that water markets and pricing improves climate change adaptation (Medellin-Azuara et al. 2008). In many cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that adaptation will be needed.

Many countries have instituted structures for water pricing in the household and agricultural sectors. Nevertheless such prices are unevenly applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user) and pricing is often based on annual rather than usage-based fees (Saleth et al., 2012). In many countries, a number of important institutional barriers to water markets and pricing remain. These include a lack of property rights including an thorough consideration of historical and current entitlements, limits on transferability, legal and physical infrastructures and institutional shortcomings (Turral et al. 2005 ; Saleth et al. 2012) coupled with issues involved with return flows, third part impacts, market design, transactions costs, and average versus marginal cost pricing (Griffin, 2012).

17.5.4. Charges, Subsidies, and Taxes

The environmental economics literature over the past 30 years has emphasized the importance of market-based instruments (MBIs) relative to command and control regulations. MBIs are shown to be generally more cost effective, providing stronger incentives for innovation and dynamic efficiency. Within the wide range of instruments that qualify as market based, there is a general preference in terms of overall efficiency for taxes over subsidies (Sterner, 2002; Barbier and Markandya, 2012). MBIs include charges on harmful emissions and wastes, subsidies to clean energy, subsidized loans and others.

In many cases climate change exacerbates the effects of pricing resources below their social costs. This is true for some forms of energy (e.g. hydro and fossil fuel-based) as well as many ecosystem services. If these resources were optimally priced, there would be greater incentives to investment in clean technologies and the need for additional public sector adaptation measures would be lessened (ESMAP, 2010).

In addition to the instruments already identified, others that are potentially important include: raising the price of energy through a tax (Sterner, 2011), developing markets for genetic resources (Markandya and Nunes, 2012) and strengthening property rights so schemes such as PES can be more effective. These measures are desirable even in the absence of climate change; they become even more so when climate impacts are accounted for. Yet it is important to note that while the case for such social cost pricing through the use of charges is strong, it also has its limitations. Higher prices for key commodities can hurt the poor and vulnerable and complementary measures may need to be taken to address such effects.

17.5.5. Intellectual Property Rights (IPR)

Technology transfer is increasingly seen as an important means of adaptation because of the global benefits it provides through the transfer of knowledge. Christiansen et al. (2011) in a Technology Needs Assessments carried out in developing countries list about 165 technological needs related to mitigation and adaptation. Examples include applications to agriculture in Cambodia and Bangladesh and coastal zones in Thailand. In many of these cases patents and other intellectual property protection constrain technology transfer. Patent buy-outs, patent pools, compulsory licenses and other open source approaches have been used to relax this constraint (Dutz and Sharma, 2012). Patent buy-outs involve third parties (e.g. international financial institutions or foundations) acquiring the marketing rights for a patented product in a developing country. Patent pools represent a group of patent holders who agree to license their individual patents to each other (closed pool) or to any party (open pool). Compulsory licenses are issued by governments and allow patent rights to be overridden in critical situations. For all the above reasons therefore, it is suggested that limits to technology transfer are limiting climate change adaptation (Henry and Stiglitz, 2010). There is also the view, however, that strong IP protection in receiving countries is facilitating technology transfer from advanced countries and the evidence indicates a systematic impact of IP protection on technology transfer through exports, FDI and technology licensing, particularly for middle-income countries for which the risk of imitation in the absence of such protection is relatively high.

17.5.6. Innovation and R&D Subsidies

Subsidies to encourage innovation through R&D may be employed as a measure to encourage adaptation investments as well as behavioral change (Bräuninger at al., 2011). Subsidies involve direct payments, tax reductions or price supports that enhance the rewards from the implementation of an activity (Gupta et al., 2007). There has been some criticism of the efficiency of subsidies in terms of rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2012). They are often poorly targeted and end up getting captured by middle and upper income groups. Moreover they imply increasing budgetary burdens. Yet they are popular with decision-makers and the wider public. Subsidies are today mostly used for reasons other than climate adaptation, and evidence regarding its use for adaptation as well as regarding the incentivizing of adaptation R&D specifically is missing.Popp, 2004 is partly an exception, which focuses on subsidies for mitigation. It shows that such subsidies have little impact on their own but they do work to enhance the effects of other instruments such as energy taxes and regulations that mandate improvements in energy efficiency the use of lower carbon options

17.5.7. The Role of Behavior

It is well recognized that often human behavior is characterized by bounded rationality, particularly in relation to choices under risk and uncertainty, which affects the effectiveness of incentive-based approaches. Individuals may over- or underestimate risks (Ellsberg 1961; Kahneman and Tversky 1979), and may not consistently weigh long term consequences (Ainslie 1975). One well documented explanation is that individuals do not fully use available information on risks when they make their choices (Magat et al., 1987; Camerer and Kunreuther, 1989; and Hogarth and Kunreuther, 1995). Policies that well consider such risk perceptions and behavioral biases increase their efficiency. For instance, people react differently to abstract information on distant events as opposed to concrete, current, emotionally-charged information (Trope and Liberman, 2003). In practice, this can limit the impact of simply communicating “dry”, emotion-free, information, such as that on flood return periods, and underlines the importance of participatory, reflexive and iterative approaches to decision-support(Fischhoff et al., 1978; Slovic, 1997; Renn, 2008; IRGC, 2010) [see also 2.1.2].

Frequently Asked Questions

FAQ 17.1: Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision-making in this area? *[to be inserted in Section 17.3]*
Economic methods have been developed to inform a wide range of issues that involve decision making in the face of uncertainty. Indeed some of these methods have already been applied to the evaluation of adaptation measures, such as decisions on which coastal areas to protect and how much to protect them.

A range of methods can be applied, depending on the available information and the questions being asked. Where probabilities can be attached to different outcomes that may result from an adaptation measure, economic tools such as risk and portfolio theory allow us to choose the adaptation option that maximizes the expected net benefits, while allowing for the risks associated with different options. Such an approach compares not only the net benefits of each measure but also the risks associated with it (e.g. the possibility of a very poor outcome).

In situations where probabilities cannot be defined, economic analysis can define scenarios that describe a possible set of outcomes for each adaptation measure which meet some criteria of minimum acceptable benefits across a range of scenarios, allowing the decision-maker to explore different levels of acceptable benefits in a systematic way. That, of course, hinges on the definition of “acceptability”, which is a complex matter that accounts for community values as well as physical outcomes. These approaches can be applied to climate change impacts such as sea level rise, river flooding and energy planning.

In some cases it is difficult to place specific economic values on important outcomes (e.g. disasters involving large scale loss of life). An alternative to the risk or portfolio theory approach can then be used, that identifies the least-cost solution that keeps probable losses to an acceptable level.

There are, however, still unanswered questions on how to apply economic methods to this kind of problem (particularly when the changes caused by climate change are large and when people’s valuations may be changed), and on how to improve the quality of information on the possible impacts and benefits.

FAQ 17.2: Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems? *[to be inserted in Section 17.4]*
A narrow economic approach can fail to account adequately for such items as ecosystem services and community value systems, which are sometimes not considered in economic analysis or undervalued by market prices, or for which data is insufficient. This can bias decisions against the poor, vulnerable populations, or the maintenance of important ecosystems. For example, the market value of timber does not reflect the ecological and hydrological functions of trees nor the forest products whose values arise from economic sectors outside the timber industry, like medicines. Furthermore some communities value certain assets (historic buildings, religious sites) differently than others. Broader economic approaches, however, can attach monetary values to non-market impacts, referred to as

externalities, placing an economic value on ecosystem services like breathable air, carbon capture and storage (in forests and oceans) and usable water. The values for these factors may be less certain than those attached to market impacts, which can be quantified with market data, but they are still useful to provide economic assessments that are less biased against ecosystems.

But economic analysis, which focuses on the monetary costs and benefits of an option, is just one important component of decision making relating to adaptation alternatives, and final decisions about such measures are almost never based on this information alone. Societal decision making also accounts for equity - who gains and who loses - and for the impacts of the measures on other factors that are not represented in monetary terms. In other words, communities make decisions in a larger context, taking into account other socioeconomic and political factors. What is crucial is that the overall decision-framework is broad, with both economic and non-economic factors being taken into consideration.

A frequently used decision-making framework that provides for the inclusion of economic and non-economic indicators to measure the impacts of a policy, including impacts on vulnerable groups and ecosystems, is multi-criteria analysis (MCA). But as with all decision making approaches, the a challenge for MCA and methods like it is the subjective choices that have to be made about what weights to attach to all the relevant criteria that go into the analysis, including how the adaptation measure being studied impacts poor or vulnerable populations, or how fair it is in the distribution of who pays compared to who benefits.

FAQ 17.3: In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries? *[to be inserted in Section 17.5]*

Economic instruments (EIs) are designed to make more efficient use of scarce resources and to ensure that risks are more effectively shared between agents in society. EIs can include taxes, subsidies, risk sharing and risk transfer (including insurance), water pricing, intellectual property rights , or other tools that send a market signal that shapes behavior. In the context of adaptation, EIs are useful in a number of ways.

First, they help establish an efficient use of the resources that will be affected by climate change: water pricing is an example. If water is already priced properly, there will be less overuse that has to be corrected through adaptation measures should supplies become more scarce.

Second, EIs can function as flexible, low-cost tools to identify adaptation measures. Using the water supply example again, if climate change results in increasing water scarcity, EIs can easily identify adjustments in water rates needed to bring demand into balance with the new supply, which can be less costly than finding new ways to increase supply.

Insurance is a common economic instrument that serves as a flexible, low cost adaptation tool. Where risks are well-defined, insurance markets can set prices and insurance availability to encourage choices and behaviors that can help reduce vulnerability, and also generate a pool of funds for post-disaster recovery. Insurance discounts for policy holders who undertake building modifications that reduce flood risk, for example, are one way that EIs can encourage adaptive behavior.

Payments for environmental services (PES) schemes are another economic instrument that encourages adaptive behavior. This approach pays landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change mitigation and adaptation. A PES approach is being used in Costa Rica to manage natural resources broadly, for example. Paying timber owners not to cut down forests that serve as carbon sinks (the idea behind the REDD proposal to the UNFCCC), or paying farmers not to cultivate land in order reduce erosion damage (as is being done in China and the US), are examples. In developed countries, where markets function reasonably well, EIs can be directly deployed through market mechanisms. In developing countries (and also in some developed ones), however, this is not always the case and markets often need government action and support. For example, private insurance companies sometimes don’t cover all risks, or set rates that are not affordable, and public intervention is required to make sure the insurance is available and affordable. Government also has an important role in ensuring that voluntary market instruments work effectively and fairly, through legal frameworks that define property rights involving scarce resources such as land and water in areas where such rights are not well established. An example of this is the conflict between regions over the use of rivers for water supply and hydropower, when those rivers flow from one jurisdiction to the next and ownership of the water is not clearly established by region-wide agreements. PES schemes can only function well when the public sector ensures that rights are defined and agreements honored.

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Table 17-1: Four definitions of eligible adaptation.

Relevant climatic factors **Motivation for action**	**Observed and/or projected climate change**	**Climate change as well as natural climate variability**
Climate is the main reason	**Definition 1:** Action occurs mainly to reduce the risks of observed or projected climate change **Example:** Raising of existing dykes	**Definition 2:** Action occurs mainly to reduce risks of climate change and climate variability **Example:** Building of new dykes in areas that are currently unprotected
Climate is one of several reasons	**Definition 3:** Actions that reduce the risks of observed or projected climate change even if they are also justified in the absence of climate change **Example:** Economic diversification in predominantly agricultural regions	**Definition 4:** Actions that reduce the risks of climate change and climate variability even if they are also justified in the absence of climate change **Example:** Improved public health services

Source: Füssel et al. (2012), adapted from Hallegatte (2008).

Table 17-2: Estimates of global costs of adaptation.

Study	**Results (billion USD/year)**	**Time frame**	**Sectors**	**Methodology and comment**
World Bank, 2006	9-41	Present	Unspecified	Cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA)
Stern, 2007	4-37	Present	Unspecified	Update of World Bank (2006)
Oxfam, 2007	>50	Present	Unspecified	WB (2006) plus extrapolation of cost estimates from national adaptation plans (NAPAs) and NGO projects.
UNDP, 2007	86-109	2015	Unspecified	WB (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC, 2007	28-67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and Financial Flows required for the international community
World Bank, 2010a	70-100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement upon UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea-level rise and storm surges.

Source: Modified from Agrawala and Fankhauser (2008) and Parry et al. (2009) to include estimates from World Bank (2010a).

Table 17-3: Coverage of adaptation costs and benefits.

Sector	Analytical Coverage	Cost Estimates	Benefit Estimates
Coastal Zones	Comprehensive	√√√	√√√
Agriculture	Comprehensive	-	√√√
Water	Isolated case studies	√	√
Energy	N. America, Europe	√√	√√
Infrastructure	Cross-cutting, partly covered in other sectors	√√	-
Health	Selected impacts	√	-
Tourism	Winter tourism	√	-

Note: Three checks indicates good to excellent coverage of the topic in the literature; two checks indicates medium coverage; one check indicates limited coverage; the absence of a check indicates extremely limited or no coverage. Note that indicators reflect literature review through publication of source in 2008. Source: Agrawala and Fankhauser (2008).

Table 17-4: Studies illustrating economic evaluation of adaptation options.

Sector, Study, and Scope	Methodology	Key Points Illustrated
Agriculture, Forestry, and Livestock		
Seo and coinvestigators (e.g. Seo et al , 2008b, 2009b, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate Insights into adaption possibilities by examining the ways economic choices vary over locations and times with varying climate conditions.	Consideration of multiple options (implicit) Residual impacts reflected Applicable at multiple geographic scales Results provide a ready means to re-estimate results for multiple climate scenarios.
Butt et al. (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	Broad consideration of options (explicit, allowing for ranking of measures) Residual impacts reflected Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security.
Sutton et al (2013): Crop and livestock sector in four Eastern European and Central Asian countries	Simulation with benefit-cost analysis. Ranks options initially based on net economic benefits over 2010 to 2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	Broad consideration of options (explicit, measures ranked) Very broad representation of climate scenarios (56 GCM-SRES combinations) Rigorous economic costing of adaptation options Integrated analysis of agriculture and irrigation water sectors
Sea-level Rise and Coastal Systems		
Nichols and Tol (2006):Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study, reflects an economic decision-rule for most categories and benefit-cost analysis for a few categories	Capable of broad representation of sea-level rise scenarios. Optimization of alternatives considering both the impact of adaptation and resulting residual impacts. Rigorous economic costing of adaptation options.
Neumann et al. (2010a): Risks of sea-level rise for a portion of the coastal United States	Simulation of adaptation decision-making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit-cost framework but with alternatives based on local land-use decision-making rules.`	Capable of broad representation of sea-level rise scenarios Flexibility to consider both benefit-cost and rule-based decision making Rigorous and dynamic economic costing of adaptation options
Purvis et al. (2008): Risks of coastal flooding in Somerset, England	What is adaptation strategy here Simulation using a probabilistic representation to characterize uncertainty in future sea-level rise and, potentially, other factors that could affect coastal land-use planning and development investment decisions	Considers the impact of both gradual climate change (sea-level rise) and extreme events (the 1 in 200 year recurrence interval coastal flooding event). Incorporates probabilistic uncertainty analysis
Water		
Ward et al. (2010): Future needs and costs for municipal water across the world, scalable to national and local scale	Assesses costs with and without climate change of reaching a water supply target in 2050. The aggregation level used is the food producing units level, and storage capacity change, using the secant peak algorithm to determine the storage yield relationship and the cost of various alternative sources of water. Find that baseline costs exceed adaptation costs ($73 billion per year versus $12 billion per year for adaptation), with most of the adaptation costs (83-90%) incurred in developing countries.	Multiple climate scenarios Scalable to multiple spatial resolutions, with national and regional results reported Multiple alternative adaptation options considered Rigorous economic costing of site-specific capital and operating costs

Urban Flooding		
Ranger et al. (2011): direct and indirect impacts of flooding in Mumbai, India	Investigates the consequences of floods with different return periods, with and without climate change; the effect of climate change is from a weather generator that downscales simulations from a global climate model. Estimates direct losses from a 100-yr event rising from $600 million today to $1,890 million in the 2080's, and total losses (including indirect losses) rising from $700 to $2,435 million. Impacts give rise to adaptation options, some targeting direct losses (e.g., improved building quality, improved drainage infrastructure) and others targeting indirect losses (e.g., increased reconstruction capacity, micro-insurance). Analysis finds that improved housing quality and drainage could bring total losses in the 2080's below current levels and that full access to insurance would halve indirect losses for large events.	Considers multiple adaptation options Explicitly considers both direct and indirect costs Rigorous economic costing of adaptation options
Energy		
Lucena et al. (2010): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production	Considers two GHG emissions scenarios and a "no-climate change" baseline Scalable to multiple spatial resolutions, with national and regional results reported Considers multiple adaptation strategies Rigorous economic costing of capital and recurring adaptation costs
Health		
Ebi (2008): Global adaptation costs of treatment of diarrhoeal diseases, malnutrition, and malaria	What is the adaptation considered The costs of three diseases estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	Multiple climate scenarios Clear description of framework and key assumptions Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty
Macroeconomic analysis		
De Bruin et al. (2009b): Adaptation strategies compared to mitigation strategies within the context of a global integrated assessment model	Use of an integrated assessment model (the DICE model) with refined adaptation functions. Examines the efficacy of "stock" adaptations (mainly infrastructure) adaptations versus "flow" adaptations (mainly operational or market responses), with comparisons to mitigation investments.	Multiple climate scenarios Clear description of framework and key assumptions Considers multiple adaptation strategies Rigorous economic costing of adaptation options
Margulis et al. (2011): Climate change impacts in the economy	Use of a general equilibrium (GCE) model to simulate two climate change-free scenarios regarding the future of Brazil's economy. Climate shocks were projected and captured by the model through impacts on the agricultural/livestock and energy sectors. The socio-economic trends of the scenarios with and without global climate change were reviewed in terms of benefits and costs for Brazil and its regions.	The economic impacts of climate change are experienced across the business sectors, regions, states, and large cities and were expressed in terms of GDP losses. The simulation disaggregates results for up to 55 sectors and 110 products and also provides macro-economic projections as inflation, exchange rate, household sector consumption, government expenditures, aggregate investment, and exports. It also includes expert projections and scenarios on specific preferences, technology and sector policies.

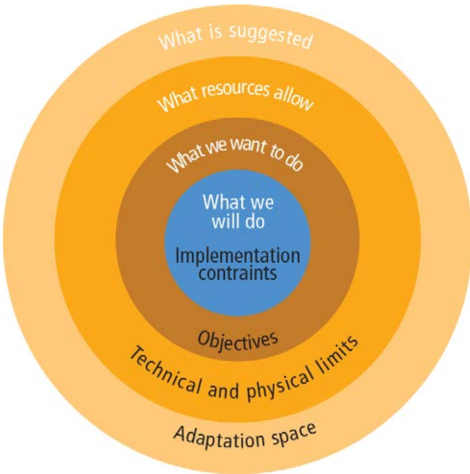

Figure 17-1: The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.

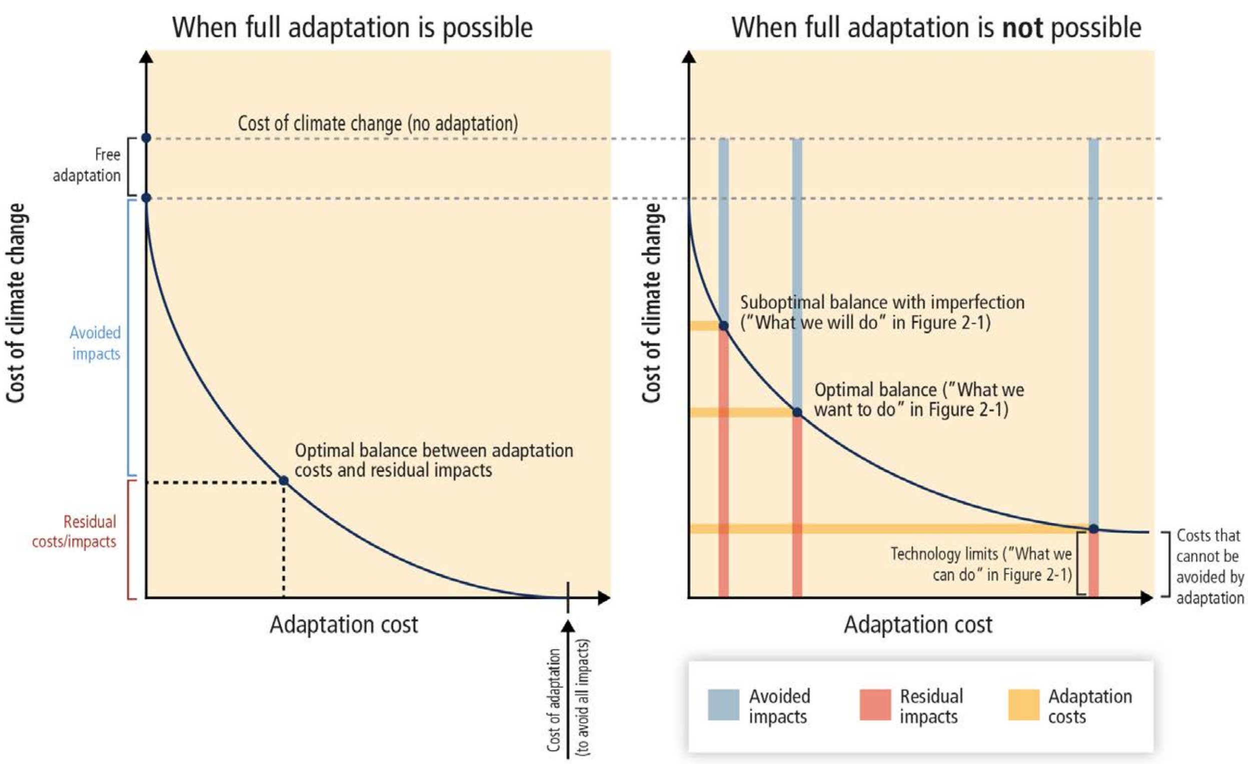

Figure 17-2: Graphical representation of link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.

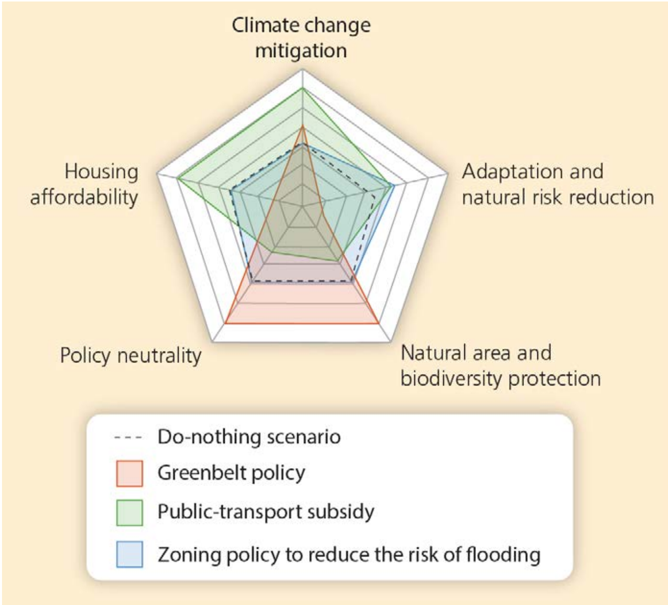

Figure 17-3: Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using 5 different metrics representing 5 policy objectives. Axes orientation is such that directions towards the exterior of the radar plot represent positive outcomes. Source: Viguié and Hallegatte, 2012.

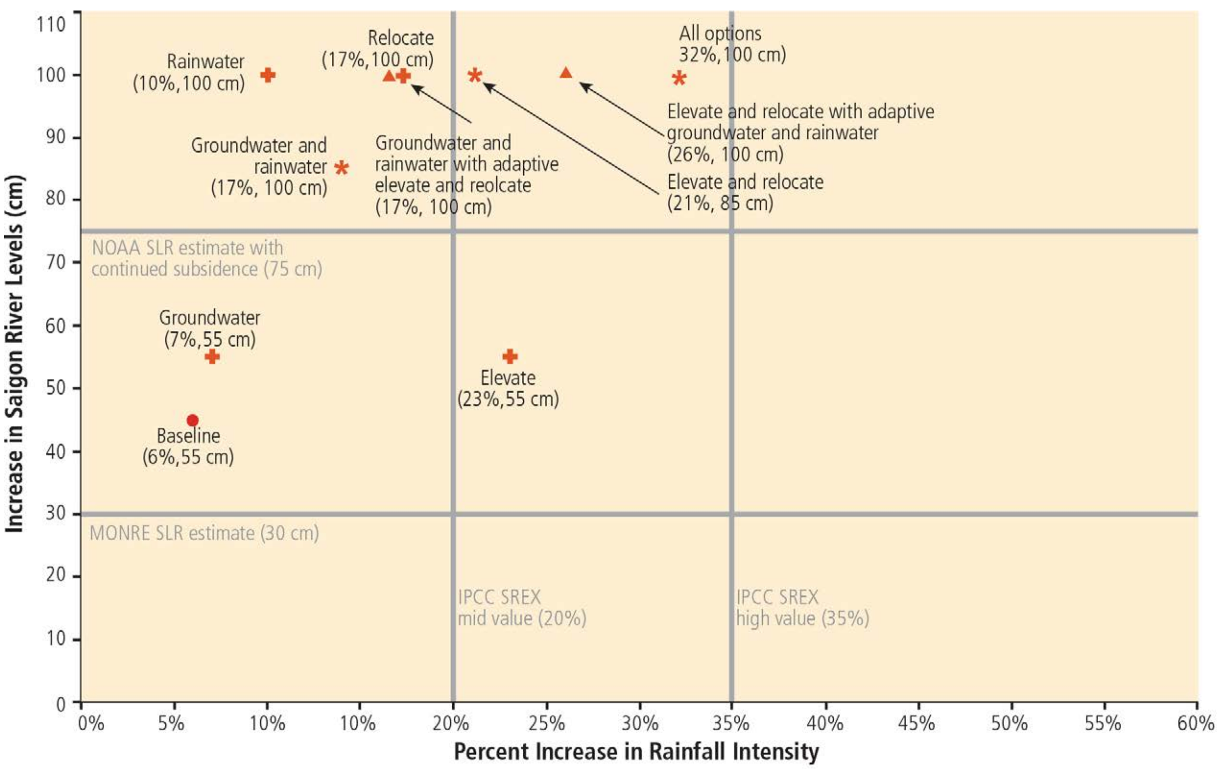

Figure 17-4: Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change. Source: Lempert et al., 2013.

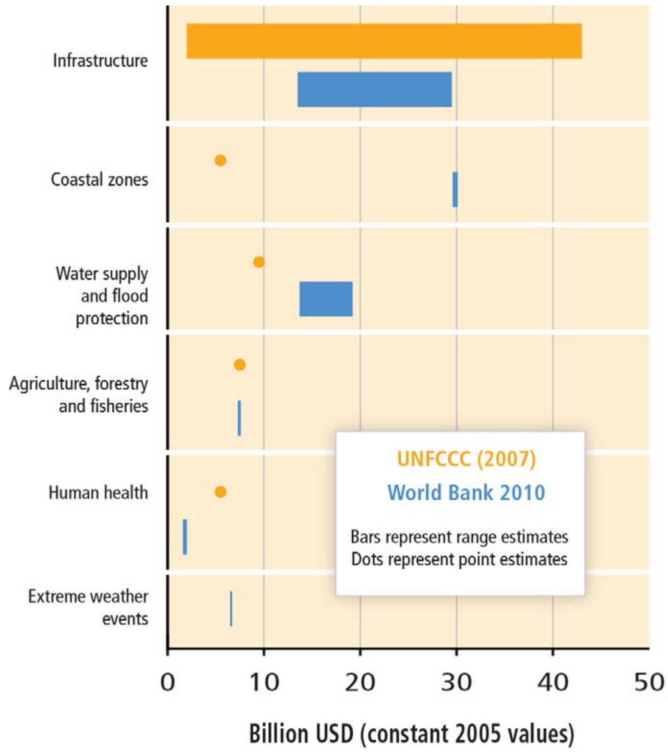

Figure 17-5: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, points indicate point estimates.