The Costs and Benefits of Adaptation

Results from the ECONADAPT project

Funded by
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Policy Report

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

Key Messages

This policy summary synthesises the evidence base on the costs and benefits of adaptation. It draws on the research, analysis and review of the ECONADAPT project, funded by the European Union's Seventh Framework Programme. The key messages are summarised below.

• The knowledge base on the costs and benefits of adaptation has evolved significantly in recent years. There are now many more studies at national, regional and local scale, with coverage in both developed and developing countries.

• In terms of the coverage by sector and risk, estimates of the costs and benefits of adaptation have moved beyond the previous focus on coastal zones and now extend to water management, floods, agriculture and the built environment. However, major gaps remain for ecosystems and business/services/industry.

• The methods for identifying options and assessing costs and benefits have also changed. More recent studies use iterative climate risk management, which puts more emphasis on current climate variability for the short-term, as well as future risks and uncertainty for the long-term.

• The focus of more recent studies has been on different types of adaptation, with a greater emphasis on early low-regret options, including capacity building and non-technical options. Many recent studies are also shifting to decision making under uncertainty, using new economic appraisal approaches. However, the wide range of methods and approaches now in use makes direct comparability between studies challenging.

• More recent implementation-based and policy-orientated studies indicate higher costs of adaptation than the previous literature. This is because these studies address existing policy objectives and standards, they consider multiple risks and recognise and plan for uncertainty, and they include the additional opportunity and transaction costs associated with policy implementation.

• While important gaps exist in the empirical evidence, and there are emerging issues overthe transferability of estimates, the new evidence base provides an increased opportunity for sharing information and good practice.

• A full version of the review on the costs and benefits of adaptation is available at the ECONADAPT project web-site, www.econadapt.eu

ECONADAPT

The ECONADAPT project (Economics of Adaptation) is a research project funded by the European Union Seventh Framework Programme (FP7). The objectives are to build the knowledge base on the economics of adaptation to climate change and to convert this into practical information for decision makers, in order to help support adaptation planning.

To advance these objectives, the project is focusing on key methodological issues and producing empirical data for a range of adaptation problems, and centring the research on the main challenges for European adaptation. The project frames the overall research by asking two questions, each addressed in a separate but linked work -stream.

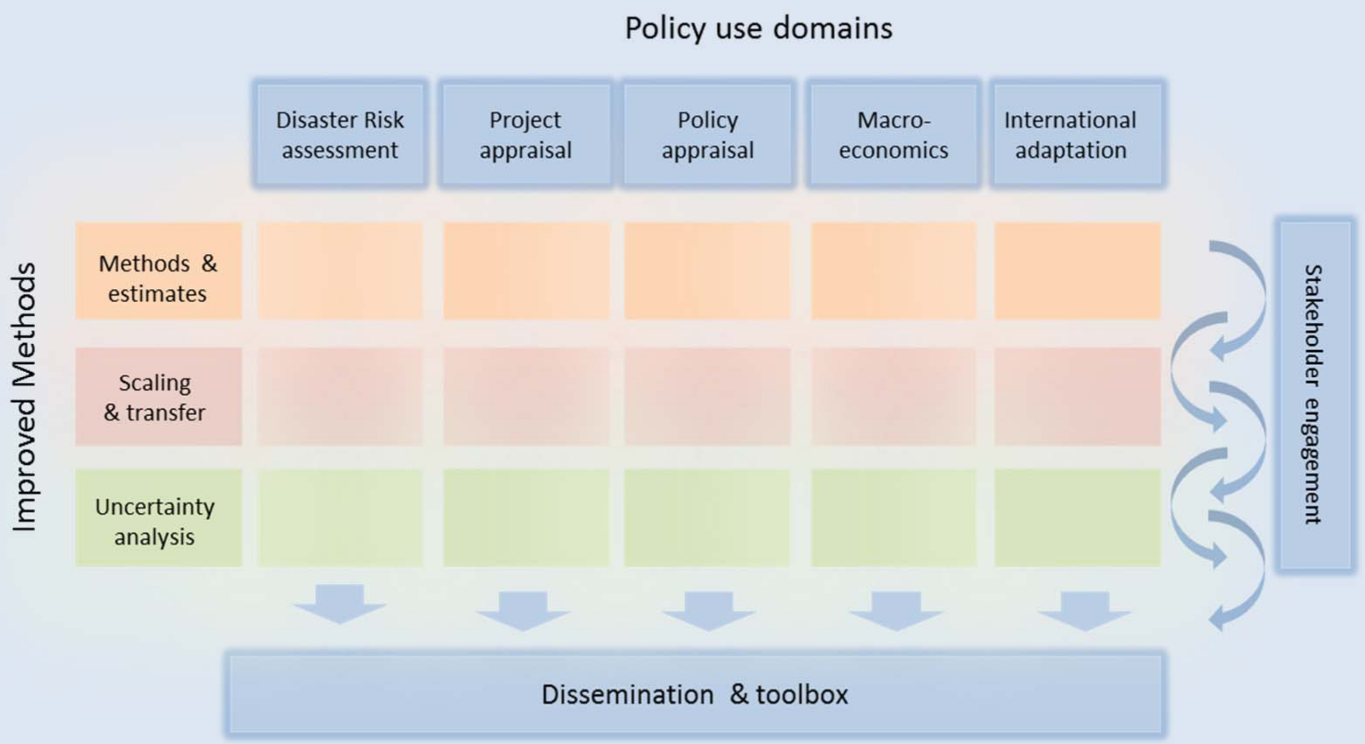
• First, what are the key methodological advances needed to improve the economic assessment of adaptation?

• Second, what are the big adaptation decisions facing Europe in the next decade where these improved economic methods could be applied?

The first stream of research therefore focuses on improving the analytical methods to tackle the challenges of adaptation and to enhance the information base. The second stream frames the project from an end-user perspective, focusing on those areas (policy domains) which are likely to need more advanced economic analysis of adaptation. The two streams are combined together as shown in the Figure below.

The ECONADAPT has also adopted a policy-centred approach. The research incorporates stakeholder involvement throughout the project, and a series of policy workshops are planned to ensure a dialogue with potential end-users. The project will develop a toolbox that provides guidance on the methodological approaches and summarises the case study findings.

The ECONADAPT project commenced in October 2013 and will run for 36 months. To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu



Introduction

This policy report synthesises the estimates and evidence base on the costs and benefits of adaptation at the global, national, regional and local scale. It draws on the research, analysis and review of the ECONADAPT project, funded by the European Union's Seventh Framework Programme[1] and from co-funding provided by the UK Department for International Development and by Canada's International Development Research Centre[2].

The report starts with an introduction to the frameworks and the challenges involved in estimating the costs and benefits of adaptation, as well as how methods and assumptions influence the results. It then assesses different evidence lines, looking at global, national and sectoral studies. Finally, the findings from the review are highlighted and gaps identified.

Supporting information on the costs and benefits of adaptation is available at the ECONADAPT project web-site, www.econadapt.eu.

Methods: from theory to practice

The current trends of global GHG emissions and future levels of climate change will lead to wide ranging environmental, social and economic effects, which will lead in turn to economic costs or benefits[3] in market and non-market sectors. The level of impacts (or benefits) will depend on future socio-economic pathways and climate policies, although there will still be impacts even if the goal to limit global warming to 2°C relative to pre-industrial is achieved (IPCC, 2014a).

Adaptation - the process of adjustment to actual or expected climate - can moderate these impacts of climate change (or exploit beneficial opportunities). However, it has a cost, associated with planning, preparing, facilitating, and implementing adaptation, including policy and transition costs.

The analysis of costs and benefits of adaptation therefore has an important role in justifying the case for action, and for considering how to prioritise available resources to deliver greatest social, environmental and economic benefits. Information on the costs and benefits of adaptation is potentially relevant at a number of aggregation levels, addressing different objectives:

- At the global level, this information can be used to raise awareness, and to provide an input to the discussion on international financing needs.

- At the national level, it is relevant for national adaptation strategies, plans and financing needs, as well as for prioritisation decisions on adaptation policies and programmes to allow efficient, effective and equitable response strategies.

- At the local level, it can assist in the design and prioritization of adaptation policies, programs and projects, including in appraisal.

In theory, a common framework can be used for the analysis of costs and benefits at all three aggregation levels (Boyd et al., 2004: Stern et al., 2006) and this has been widely adopted in the literature. This framework first assesses the impacts and economic costs of climate change – including from slow onset trends and changes in extreme events. It then assesses the potential costs and benefits of adaptation to reduce these impacts. This information can be used to assess the economic effectiveness of adaptation, i.e. whether the economic benefits of adaptation outweigh the costs and even the optimal response. It can also be used to compare alternative adaptation options.

There is, however, an additional step to undertake in this analysis. This assesses the residual impacts of climate change after adaptation, noting that it will rarely be completely effective – or even technically possible - to remove impacts completely:

1. The ECONADAPT project is funded by the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906. The views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission. The European Community is not liable for any use made of this information.

2. Co-funding was provided by: i) UK Department for International Development, as part of the project 'Early Value-for-Money Adaptation: Delivering VfM Adaptation using Iterative Frameworks and Low-Regret Options' - this project has been funded by UK aid from the UK government; however the views expressed do not necessarily reflect the UK government's official policies: ii) Canada's International Development Research Centre (IDRC), as part of the project 'The Economics of Adaptation and Climate-Resilient Development' – however the views expressed in this report are entirely those of the authors and do not necessarily reflect the views of IDRC.

3. It is highlighted that this book concentrates on the economic costs of climate change and the costs and benefits of adaptation, rather than the financial costs. Economic costs capture the wider costs and benefits to society as a whole, including those elements not valued directly by markets.

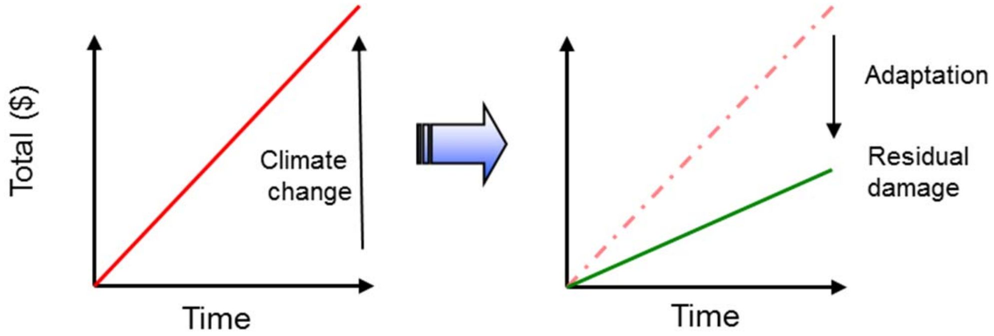


Fig. 1. Stylised framework for assessing adaptation benefits

Source: UNFCCC, 2009

The most effective (or optimal) level of adaptation will therefore be a balance between the costs of adaptation, the benefits of adaptation and the residual impacts.

A number of methods have been developed to derive estimates of the costs and benefits of adaptation (see Watkiss and Hunt, 2010, for a review), essentially using the framework outlined above. These primarily use some form of impact assessment, either with Integrated Assessment Models (IAM) at the global scale, or scenario-based impact assessment (or risk assessment or Ricardian [econometric] based analysis) at the national to local scale. Such approaches have formed the basis for the literature in previous reviews of costs and benefits.

However, the simple theoretical framework above – and the estimates from models that are based on it - runs into a number of major challenges in practice.

First, the economic costs of future climate change are extremely difficult to estimate. The 5th Assessment Report (IPCC, 2014b) reports incomplete estimates of global annual economic losses for temperature increases of ~2°C are between 0.2 and 2.0% of income, but also highlights that these losses accelerate with greater warming. However, these estimates need to be treated with caution: they only represent a partial coverage of risks and impacts, and omit the likelihood of severe and irreversible impacts (non-linear tipping points/elements) that will be beyond the limits of adaptation.

They also involve contentious issues around the aggregation of impacts and benefits across time and space, and across winners and losers, noting that in practice there are no mechanisms to allow such transfers: an issue which is critical for national adaptation costs (UNEP, 2014). These global estimates are also influenced by assumptions of discount rate and equity (distributional weights), noting these issues have been highly contentious (though they are less of an issue at the national to sub-national level for early adaptation, because of the shorter policy time-frames and existing sectoral practice).

Second, there is high uncertainty over the level of climate change that will occur, and thus how much adaptation is potentially needed (UNFCCC, 2009; Hallegatte, 2009). At the current time it is not clear if the world is on a 2, 3 or even 4°C pathway – and even if this were known – there would remain high uncertainty due to the wide range of projections from different climate models. Including this uncertainty has a major influence on actions and costs, as compared to analysis where the future is assumed with foresight and an if-then [predict and optimise] framework is applied.

Third, there are potentially different objectives for adaptation, representing the balance between adaptation costs/benefits and residual impacts (Parry et al., 2009). These objectives will vary with the framing adopted, and whether this is defined by economic efficiency (and the optimal balance of costs, benefits and residual impacts), levels of acceptable risks, equity, etc. The level of adaptation thus involves ethical and subjective decisions, as well as scientific elements. As a result, it is very difficult – indeed impossible - to provide a single definitive cost of adaptation - i.e. it depends.

Fourth, the future impacts of climate change arise on top of current climate variability and extremes, i.e. the existing adaptation deficit (defined in the AR5 as the gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability). This adaptation deficit is not primarily caused by anthropogenic climate change, but adaptation (to future climate change) will be less effective if these deficits have not first been addressed (Burton, 2004). However, it is not economically efficient to reduce the adaptation gap to zero (indeed, even highly developed countries have an adaptation deficit, e.g. CCC, 2011). The critical issue therefore is whether the existing adaptation gap is sub-optimal. These issues are much more important in developing country case, where the gap is larger, but this also leads to issues of what should be counted as the development gap and what as the adaptation gap (at least with respect to marginal climate finance).

Finally, a large body of theoretical and practical literature (e.g. Füssel and Klein, 2006; UNFCCC, 2009; Ranger et al; 2010; Watkiss and Hunt, 2011) have identified that while these impact-assessment based approaches are useful for raising awareness, and generating headline estimates of the costs and benefits of adaptation, they are not useful for practical (early) adaptation.

This is because they are highly stylized studies. They have insufficient consideration of immediate and short term time-scales of relevance for early adaptation, and they do not consider wider (non-climatic) drivers and existing policy. Furthermore, they focus on a narrow set of technical adaptation responses, where unit cost estimates are available, excluding options such as capacity building, and they ignore the factors determining the adaptation process itself, including socio-institutional policy context, actors and governance. They also do not adequately consider uncertainty because they focus on the adaptation response (solution) to defined future projections, considering the adaptation cost for individual future climate change projections one at a time.

This predict-and-optimise approach therefore presents information on how adaptation responses might change with uncertainty, but it does not inform the policy maker on what to do now, given this future uncertainty exists. Finally, they have a highly theoretical perspective, which assumes adaptation is completely effective and ideally implemented, within an effective governance and implementation framework.

As a result, the recent literature concludes that impact-assessment driven studies – on their own - do not provide the necessary information for practical- and policy orientated adaptation, i.e. for early implementation.

These challenges have major implications for adaptation cost and benefit assessments and estimates, especially when moving to practical adaptation implementation. In response, the framing of adaptation has changed considerably over recent years, as reflected in the IPCC SREX (IPCC, 2012) and 5th Assessment Report (IPCC, 2014a). This has been accompanied by an observable shift in the literature on adaptation – and increasing adaptation costs and benefits.

There is now more focus on policy-orientated studies - where the analysis is directed towards adaptation as the policy objective, i.e. to inform what to do now, rather than considering adaptation at the end of a classic science-first, impact-assessment study for future time periods in mid or late century.

This change, where the overall objective is considered from the perspective of informing adaptation – has been termed a 'policy-first' approach (Ranger et al., 2010). Critically, this requires a greater understanding of current drivers, non-climate policy and existing adaptation, i.e. a practical and 'real-world' policy focus. The greater emphasis on climate mainstreaming, which focuses on integrating climate adaptation into wider policies and plans rather than treating it as a stand-alone activity, makes this particularly important.

Alongside this there has been recognition that climate adaptation does not involve one single response (i.e. a technical solution to a future climate risk). Instead there has been a greater focus on identifying types of adaptation. These adaptation responses (or problem types) are often presented as a set of building blocks or a spectrum of options over time (McGray, et al, 2007; Klein and Persson, 2008). These break-down adaptation activities into early activities associated with addressing current vulnerability and building adaptive capacity, then more long-term elements associated with mainstreaming climate risks, and finally the preparation for tackling longer-term challenges. These approaches have translated into practical frameworks for identifying and analysis adaptation (e.g. see Hinkel and Bisaro, 2014).

This recognition of the timing and phasing of adaptation interventions, taking account of future uncertainty, is critical. The shift has been captured in the literature through new frameworks that identify early policy relevant decisions, i.e. those which are needed and justified (in economic terms) in the next decade to enhance climate resilient development (see Ranger et al. (2010); Fankhauser et al., 2010; Watkiss and Hunt (2011); Fankhauser et al. (2013); DFID (2014)). This aligns to the concept of adaptive management, an evaluation and learning process to improve future strategies and decisions, defined as iterative climate risk management in the IPCC 5th Assessment Report (2014). Most of these frameworks identify three broad types of early adaptation.

First, immediate actions that address the current adaptation deficit and also build resilience for the future. This involves early capacity-building and the introduction of low- and no-regret actions, noting these provide immediate economic benefits: such actions are usually grounded in current (development) policy and can often use existing decision support tools.

Second, the integration of adaptation into immediate decisions or activities with long life-times, such as infrastructure or planning.

This involves a greater focus on climate risk screening and other elements to avoid future lock-in, as well as a the introduction of flexibility or robustness to cope with uncertainty.

Finally, there is often an immediate need to start planning for the future longer-term impacts of climate change, noting the high uncertainty. This includes a focus on the value of information and future options/ learning, especially when decision life-times are long or future risks are very large or irreversible.

These interventions can be combined to give an overall portfolio of actions, or an adaptation pathway, as part of an adaptive management framework.

As a result, new methodological approaches are being used for assessing adaptation costs and benefits. For example, there is now a literature (and estimates) using investment and financial flow analysis, which estimate short-term adaptation costs by studying the increase needed over and above current and planned development or strategies: these align much more closely to existing baselines and policy. Most recently, there are economic studies emerging that use different economic tools and methods, such as real options, to consider uncertainty.

These changes have major implications for this review. It is now very difficult to compile and compare estimates of adaptation costs and benefits, because of the different methods now in use. Studies use different metrics, modelling approaches and assumptions, and often focus on different time periods. This also makes aggregation of estimates extremely challenging.

No one method is right or wrong – and they all have strengths and weaknesses – which will vary with the application. Nonetheless, there is a major difference between earlier studies (and estimates) that are based on an impact-assessment versus those that are grounded in the new policy-centred literature, which considers phasing, timing and uncertainty.

To address this, when reporting and reviewing adaptation costs and benefit estimates in this book, we highlight the method of the study and outline the types of adaptation options. The focus is on providing an updated compilation of how the state-of-the-art is changing, and the lessons and implications from the new evidence base.

Current literature

Over the past few years, there have been a number of reviews of the costs and benefits of adaptation (EEA, 2007; OECD, 2008; UNFCCC, 2009; Watkiss et al., 2010; Agrawala et al., 2011: Markandya et al., 2014; IPCC, 2014c). These reviews generally report that the evidence base is relatively low. Over more recent years, however, additional evidence has emerged.

First, there have been a large number of global assessments which have advanced national-level estimates of the costs of climate change and the cost and benefits of adaptation: varying from one or two key sectors through to economy wide assessments.

Second, there are more studies that focus on early adaptation, considering the application of existing options to new contexts or locations. As these focus on existing options, there is often ex ante or ex post economic information available on their costs, as well as their effectiveness and potential benefits.

These two factors have led to a much larger number of studies – and evidence– on the costs and benefits of adaptation. These have been collated as part of the ECONADAPT study, and over 500 relevant studies have been identified. This book summarises this new evidence base and analyses the findings.

The following sections compile the evidence and lessons, starting with the global assessments, and then providing national and risk/sectors estimates.

It is stressed that while the review has aimed to be as comprehensive as possible, this is a rapidly evolving field, and there will inevitably be additional relevant studies.

Global Estimates

A number of methods have been used to derive the potential global costs of adaptation.

Impact assessment / investment and financial flow analysis

Early work on the global costs of adaptation focused on the near to medium term (2020 to 2030), as an input to the international negotiation discussions around finance commitments, notably in the run-up to Copenhagen in 2009. Six assessments were undertaken (see Agrawala and Fankhauser, 2008) that primarily applied investment and financial flow analysis, deriving estimates by applying an adaptation 'mark-up' on current and future investment/finance levels. These studies have the advantage of grounding the analysis in current policy and plans, but they have a less direct link to future climate change and uncertainty.

The most comprehensive of these was the UNFCCC (2007) study. This estimated the potential increase in global investment needs for adaptation at $50 to $170 billion/year by 2030 (0.06 - 0.2% of projected GDP), with the largest proportion of global costs associated with infrastructure protection in developed countries, and only $30 to $70 billion/year anticipated in developing countries (Non-Annex1 parties).

However, a critique by Parry et al. (2009) argued that these estimates in this study underestimated adaptation costs by a factor of 2 to 3 for the sectors considered, and stressed a large number of additional sectors and impacts were not included.

A subsequent assessment - focusing on developing countries - was undertaken by the World Bank in their Economics of Adaptation to Climate Change (2010) study, and this was the principle study referenced in the recent IPCC (IPCC, 2014c) on the potential global costs of adaptation. This study used an impact assessment approach to estimate the economic costs of climate change, then estimated the costs of adaptation to achieve pre-climate levels of welfare (i.e. so that there were no residual impacts above the baseline). The estimated total cost for developing countries was in the range of $(2005) 70 billion to $100 billion a year (the average between 2010 and 2050, for a 2°C warmer world) and is the same order of magnitude as current foreign aid. This estimate is slightly higher than the UNFCCC study for similar regions.

Adaptation cost estimates for each developing country region – and by sector - in the dry and wet scenarios (2005 $ billions, no discounting)

Region	X sum DRY scenario	Gross sum WET scenario
East Asia & Pacific	17.9	25.7
Central Asia	6.9	12.6
Latin America & Caribbean	14.8	21.3
Middle East/ North Africa	2.5	3.6
South Asia	15.0	17.1
Sub-Saharan Africa	14.1	17.1
Total	71.2	97.5

Sector	Dry (X-sum)	Wet (X–sum)
Infrastructure	13.0	27.5
Coastal zones	27.6	28.5
Water supply and flood protection	19.7	14.4
Agriculture, forestry, fisheries	3.0	2.5
Human health	1.5	2.0
Extreme weather events	6.4	6.7
Total	71.2	81.5

Source: World Bank, 2010. # World Bank shows cost of adaptation over period 2010 – 2050. The two values shown reflect the variation across the climate projections (from the underlying NCAR and CSIRO projections). Note: The X-sums net positive and negative items within countries but not across countries and include costs for a country in the aggregate as long as the net cost across sectors is positive for the country.

The study reported rising costs over time, increasing from $60 to $70 billion /year for the period 2010 – 2019 up to $90 to $100 billion/year by 2040 – 2049, and considered two climatic futures, with minimum and maximum temperature and 'wetter' and 'drier' outcomes for rainfall, finding that higher costs arose with wetter scenarios due to impacts on infrastructure. The choice of aggregation rule also affected the estimates, notably whether gains from climate change were added to adaptation costs. The highest costs were found in East Asia and the Pacific Region, and for infrastructure, coastal zones and water sector. The study included an explicit consideration of future development baselines, and the effects of climate change by sector, and did consider (climate) uncertainty.

However, as the report acknowledges, adaptation costs were still calculated as though decision-makers know the future with certainty, with estimates calculated for each discrete projection in turn: in reality costs would be higher due to the need to hedge against a range of outcomes. Moreover, the criticisms of the UNFCCC study (from Parry et al., 2009) also apply for these estimates, i.e. the coverage of impacts and sectors are partial. All of these factors suggest the estimates are likely to be a lower bound: a point highlighted by the recent synthesis of global versus country studies from the UNEP adaptation gap report (2014).

Integrated assessment models

An alternative set of insights have been derived from global economic integrated assessment models. These combine the scientific and economic aspects of climate change within a single, integrated analytical framework, which can be used to quantify the economic impacts of climate change, and in some cases, the costs and benefits of adaptation. These tend to focus on the medium to long-term, and have been used to assess adaptation costs under different future scenarios, with and without mitigation.

The analysis is usually performed by defining the optimal combination of mitigation, adaptation and residual damage (cost efficiency) or defining optimal adaptation assuming a specific mitigation effort (cost effectiveness). Recent summaries of such studies include Agrawala et al. (2011a, 2011b) and Bosello (2014).

The results from these models obviously reflect the calibration of future impacts of climate change, and also the costs and benefits of adaptation, all of which are highly uncertain.

Therefore the modelling insights they provide should not be seen as definitive estimates of costs and benefits of adaptation, but rather qualitative indications on how such costs could evolve in the future, interacting with other policy or social economic drivers.

Most studies – and the estimates in the literature – are based on a small number of models.

Some of the early analysis was undertaken with PAGE model (Hope 1993; Plambeck et al 1997, Hope 2006, 2009). In these studies, exogenous investment (estimated outside the model) in adaptation increases "tolerability" to temperature increases and reduces the adverse impacts of climate change (when temperature exceeds tolerability). This then allows a comparison of the costs and benefits of adaptation.

A further set of assessments, considering endogenous adaptation (i.e. within the model), have been developed within a group IAMs, all evolving from the basic structure of the Nordhaus et al. DICE/RICE models. These are intertemporal utility maximisation growth models which disentangle adaptation costs from an original climate cost damage function and typically include adaptation as an additional investment decision variable. Examples of such applications include the cost efficiency of anticipatory adaptation (Bosello, 2008), reactive adaptation (De Bruin et al. 2009), cost effectiveness and efficiency of anticipatory, reactive and investment in adaptive capacity (Bosello et al. 2010; Agrawala et al., 2010). Hof et al. (2009) also applied the same methodology to analyse the effectiveness of international financing of adaptation costs using the revenue from emission trading, while Bahn et al (2010) explored the effect of adaptation on the accumulation of clean capital. Bosello et al (2014) studied the effects of climate catastrophic risk on mitigation and adaptation choices, and De Bruin (2014) adaptation needs under alternative emission scenarios.

These studies generally report that adaptation is very effective, with high benefits when compared to costs (e.g. Hope, 2009: de Bruin et al., 2009: Carraro et al., 2009: Agrawala et al., 2011a; Agrawala et al., 2011b; Bosello et al., 2013; Dellink et al., 2014), though the estimates of the global costs of adaptation from these models and studies do vary significantly. They also show that adaptation cannot replace mitigation (though there is a degree of crowding out across the two strategies) especially with uncertainty about the possible future climate damages. Indeed, a series of studies report that net climate change policy costs can be minimized when mitigation and adaptation are used in combination (e.g. de Bruin et al., 2009a,b; Felgenhauer and de Bruin, 2009; Hof et al., 2009; Agrawala et al., 2010; Bahn et al., 2010; Bosello and Chen 2010).

In these studies, adaptation expenditure closely follows the dynamics of climate change damage, which in most models is a smoothly increasing, convex function. Therefore it is low initially and relevant only after the first simulated decades. Mitigation on the contrary tends to be anticipated compared to adaptation (Bosello, 2009; Hof et al., 2009; Agrawala et al., 2011b; Bahn et al., 2010). However, recent studies have questioned the validity of this functional form, especially for higher levels of climate change.

Moreover, there are a number of assumptions within the models that are important. As highlighted above, the current state of knowledge on the economic impacts of climate change area is incomplete, and therefore adaptation costs are likely to be underestimated. Furthermore, these studies make certain aggregation assumptions (across space and time) that are ethically contentious and/or assume optimistic levels of transfers (e.g. between winners and losers). The models have also been criticized (Ackerman et al, 2008; Patt et al, 2009) for the lack of technological detail and the optimistic assumptions on adaptation, and the predict and optimise based approach to adaptation (see earlier discussion) does not capture uncertainty.

Nonetheless, the models provide highly valuable insights. For example, de Bruin (2014) assessed how impacts and adaptation costs could vary along different emission pathways, finding adaptation costs rise steeply over time in a higher emission scenario and could be around twice as high in the 4-degree world scenario than they are in the 2-degree scenario, even by 2050. Other studies indicate higher adaptation needs in developing countries which, depending on the scenarios and assumptions, are estimated to be 2–4 times larger than that of developed countries (Hof et al. 2009; Agrawala et al. 2011a;b).

Finally, these economic IAM models have also been applied at the continental level, including in the ADB study (2014) on the Economics of Climate Change for South Asia. These regional studies tend to indicate higher adaptation costs than the global EACC (World Bank, 2010) and UNFCCC (2007) studies. As an example, the annual average adaptation costs (for 2010–2050) in South Asia (Bangladesh, Bhutan, India, Maldives, Nepal, and Sri Lanka) were estimated at US$30 billion to US$40 billion/year for the region.

National Estimates

One of the main levels where more evidence has emerged, since the last review, is at the national level. An indicative mapping of national level studies on the costs of adaptation is shown in the figure, compiled by the ECONADAPT project (ECONADAPT, 2015). Note that while some country assessments are multi-sectors, many of the countries coloured in the map have only undertaken detailed analysis in one or two sectors.

OECD countries

A number of national level assessments have considered adaptation costs and benefits in the OECD. In the recent survey, countries which reported that economic assessments were included in their national adaptation programmes were Netherlands and the UK, and also Slovenia.

The Netherlands and the UK reflect perhaps the most advanced examples globally, as these have evolved over many years, from early impact assessment frameworks (e.g. UK CCIR, 1993), to consider adaptation options and possible costs (UKCIP, 2004; van Ierland et al., 2006; de Bruin et al., 2009b), and finally towards advanced iterative frameworks with the Delta programme in the Netherlands (Delta Programme, 2011:2014; Eijgenraam et al, 2014) and the UK Economics of Climate Resilience and the National Adaptation Programme (Watkiss and Hunt, 2010; Frontier, 2013: HMG, 2013).

There are also national studies in other European countries that involve adaptation cost estimates. The analysis in Sweden (SCCV, 2007) presented investment and financial flow costs for several sectors, and the Bank of Greece study (BoG, 2011) assessed costs for an adaptation scenario.

Earlier work in Italy looked at the economics of adaptation and some cost-benefit analysis of options (Carraro and Sgobbi, 2008) and more recent work in Germany undertook cost-benefit analysis on 28 potential adaptation options (UBA, 2012). At the European level, there are academic studies – cited in European adaptation policy - that have considered several sectors, such as the PESETA (Ciscar et al, 2012) and ClimateCost (Watkiss et al., 2012) studies, as well as sector specific estimates (see later discussion).

In the Americas, some of the earliest work on the costs and benefits of adaptation was in Canada (Burton and Dore, 2001), which was followed by numerous studies in specific sectors and regions that included analysis of adaptation costs, e.g. Environment Canada, 2006: NRC, 2007, NRTEE, 2011). Similarly, in the USA, there are national level studies that provide estimates in specific sectors or regions, but the recent US National Assessment (2014) did not compile national adaptation costs. A recent review (Sussman et al., 2014) has compiled the current state of knowledge on adaptation costs in the US. There are also many state-level climate change-specific adaptation actions focus on planning, which includes analysis of adaptation costs.

It is stressed that the picture is constantly changing, and the map represents a snap-shot. As examples, a number of countries are moving to some consideration of adaptation costs (e.g. Austria is undertaking a new initiative on both public and private adaptation costs[1]; the Climate Change Office Spain is undertaking reviews to gather the information on costs[2], there is a second phase of assessment planned in Greece[3] and there is an initiative by the Mexican Government is preparing a tool for tool comparing the costs and benefits of adaptation measures[4].

While there is not sufficient information to assess the total costs of adaptation in OECD countries, country level information is emerging. As examples, the annual costs for future flood protection and flood-risk management in the Netherlands have been estimated to be in excess of EUR 1 billion a year for the period 2015-2050 (Delta Commissie 2008; Delta Programme 2014). Similar annual costs have been estimated for the UK (Foresight, 2004; EA 2008: 2011: ASC, 2014). In the US, estimates suggest that adaptation costs could be as high as tens or hundreds of billions of dollars per year by the middle of this century (Sussman et al., 2014). Finally, the picture continues to evolve and a growing number of countries are starting to consider the costs and benefits.

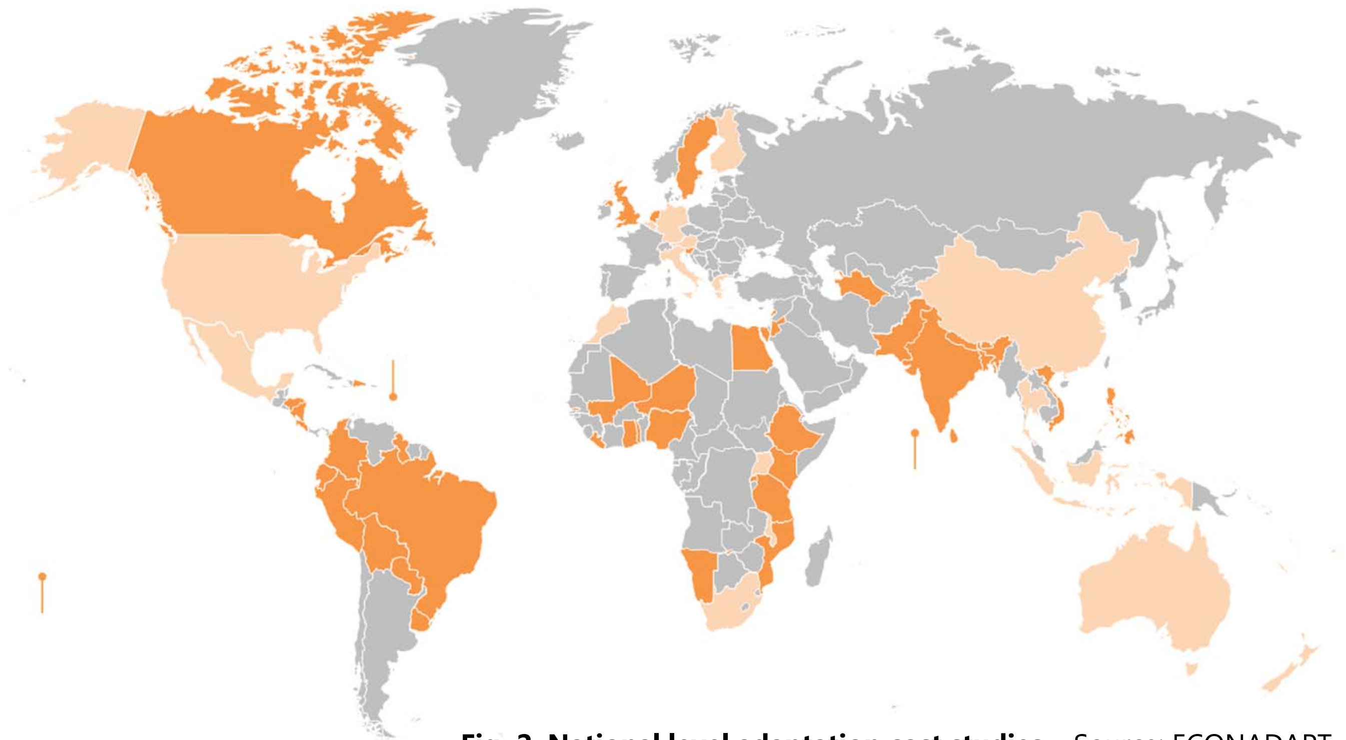


Fig. 2 National level adaptation cost studies. Source: ECONADAPT

National assessment studies and initiatives | Other studies with national or sub-national coverage

[1] Public Adaptation Costs: Investigating the National Adaptation Strategy in Austria (PACINAS) http://www.adaptecca.es/

[2] Following the first assessment of economy wide adaptation costs in 2011,

[3] The Bank of Greece has (in early 2015) embarked into an elaboration of a national adaptation strategy including an in-depth analysis of sectoral adaptation costs.

[4] https://gc21.giz.de/ibt/var/app/wp342deP/1443/index.php/knowledge/mainstreaming/examples-from-application/mexico-cost-benefit-analysis-for-prioritising-climate-change-adaptation-measures/

Developing Countries

Over recent years, a number of initiatives have emerged that provide early estimates of the costs of adaptation in non-OECED countries, primarily focused on the near – term (to 2030). These include the UNDP Assessment of Investment and Financial Flows (IFF) to Address Climate Change (UNDP, 2011), the World Bank EACC country studies (World Bank 2010), the UNFCCC National Economic, Environment and Development Study (NEEDS) (UNFCCC, 2010), the Regional Economics of Climate Change Studies (RECCS) and individual country or sector initiatives.

The seven World Bank EACC country studies (2010) (in Bangladesh, Bolivia, Ethiopia, Ghana, Mozambique, Samoa, and Vietnam) complement the EACC global estimates cited above, using the same general impact-assessment framework. However, they provide more detailed (bottom-up) assessment and allow the analysis of economy wide effects.

An alternative set of country analysis was produced under the UNDP IFF initiative, which used a different method, centred on investment and financial flows. These studies estimate the additional adaptation costs required through to 2030. A total of 15 country studies were undertaken (Bangladesh, Colombia, Costa Rica, Dominican Republic, Ecuador, Gambia, Honduras, Liberia, Namibia, Niger, Paraguay, Peru, Togo, Turkmenistan, Uruguay), focusing on 1 or 2 key sectors each (primarily agriculture and/or water).

A further study – the UNFCCC NEEDS project (in Egypt, Ghana, Jordan, Lebanon, Maldives, Mali, Philippines, Nigeria) (UNFCCC, 2010) – assessed the short- and long-term costs of adaptation financing needs. These studies also indicate high individual country estimates. The studies use different methods and time periods, and costs range from USD 161.5 million to USD 20.69 billion.

Finally, a number of other regional and country level initiatives have provided estimates (e.g. in Bangladesh (ADB, 2014). Brazil (Margulis et al., 2010), Bhutan (ADB, 2014), Caribbean (CCRIF, 2010: ECLAC, 2011a), Central America, China, Ethiopia (FDRE, 2015), Guyana (ECLAC, 2011b), Kenya (SEI, 2009), India (Markandya and Mishra, 2010: ADB, 2014), Indonesia (ADB, 2009), Maldives (ADB, 2014); Nepal (IDS, 2014: ADB, 2014), Philippines (ADB, 2009), Peru (PAC, 2013), Rwanda (SEI, 2009b), Samoa (ECA, 2009), South Africa (AIACC, 2006; Cartwright et al., 2013), Sri Lanka (ADB, 2014), Tanzania (GCAP, 2010: GoT, 2014), Thailand (ADB, 2009), Uganda (CDKN, forthcoming) and Vietnam (ADB, 2009).

Discussion

The growing number of national (and regional) level assessment is enhancing the evidence base, and providing important information for national level planning and prioritisation.

Interestingly, these national studies indicate higher adaptation costs than estimated by the global studies (irrespective of whether the global assessments are from impact assessment, investment and financial flow or integrated assessment model estimates). For example, the adaptation costs in the national UNDP IFF studies indicate costs that are almost an order of magnitude higher than the global impact assessments. Even within the EACC study itself, the costs of adaptation for countries are higher when estimated in national studies than for the same countries in the global assessments.

There are some reasons for this. As highlighted earlier, the coverage of the global studies are partial. National studies generally include a greater coverage of risks and this leads to higher estimates (though they may omit low cost market-based adaptation, such as from international trade). National studies usually also consider a wider range of climate projections: as an example the EACC (2010) study is based on funding adaptation for 2°C of climate change: higher levels of warming lead to much higher adaptation costs, even in the medium-term. Related to this, there is often more consideration of decision making under uncertainty in national studies, and this increases costs, as it requires different responses when compared to a global predict-then-optimise framework.

Finally, more practically focused studies indicate a number of cost categories are being ignored in many global estimates, notably around opportunity, transaction and policy costs. In the developing country context, the high effectiveness assumed in many studies is unlikely to be delivered, due to the existing adaptation deficit and due governance / development challenges. Furthermore, there will be significant costs associated with practical implementation (e.g. with technical assistance or project implementation and management).

While this finding is important, it is difficult to use the national studies to provide updated aggregated global estimates, because of the range of methods and assumptions used. Further work to take the lessons from these national studies, and integrate them in global assessments, is therefore a priority.

Risk-based sector estimates

Alongside the national initiatives, there are a growing number of studies focusing on specific risks or sectors, often at sub-national level.

Introduction

Previous reviews have reported and assessed estimates on a sector by sector analysis. This provides a useful entry point, but in many cases, adaptation is a response to a defined risk, which is often cross-sectoral in nature. As an example, climate extremes (such as floods or heat waves) affect multiple sectors, and there are choices on whether to adapt with individual sector initiatives or through co-ordinated responses, noting the latter can share costs, identify co-benefits, and raise potential conflicts.

For this reason, the review is primarily arranged by major risks, although it also presents discussion by sector where there are complex convergences, notably for agriculture and biodiversity/ecosystem services. In each area, the discussion sets out the potential adaptation options, the state of the literature, examples of costs level, then moves to a discussion of the more recent adaptation literature towards early implementation.

It is noted that collating and comparing these costs are benefits is challenging, because estimates are based on different objectives, methods, time periods, and often expressed using different metrics (annual values, equivalent annualised values, net present values or benefit to cost ratios) which all vary with assumed lifetimes, discount rates, uplifts and price year. Therefore the focus is not so much of absolute costs, but rather on the state-of-evidence and potential lessons and insights.

Sea-level rise, coastal flooding and storms

There are a number of potential risks from climate change on coastal zones, from a combination of sea level rise, storm surges and increased wind speeds, risks of flooding, loss of land, coastal erosion, salt water intrusion and impacts on coastal wetlands. In response there is a broad set of adaptation options – based around protection, retreat or accommodation (Nicholls, 2007).

Coastal adaptation was assessed as the most comprehensively covered area in the previous reviews of adaptation costs and benefits (OECD, 2008; Watkiss et al., 2010; Agrawala et al., 2011) and the evidence base has expanded significantly since this time.

There are a large number of studies that have used integrated sector impact-assessment (I-A) from the global to national level, notably using the DIVA coastal model (Hinkel and Klein, 2009). This considers physical barriers (dikes) to address flood risks and shoreline management (beach nourishment) to address coastal erosion. This model has provided global estimates of the costs of adaptation for coastal areas (UNFCCC, 2007, WB EACC, 2011), regional scale estimates (e.g. in Africa, Brown et al., 2009 and in Europe (Hinkel et al., 2011: Brown et al., 2011) and in many national studies (e.g. in Mozambique (WB, 2010b); Ghana (WB, 2010c); Kenya (SEI, 2009); Peru (PAC, 2014), Tanzania (GCAP, 2011) and India (Markandya and Mishra, 2010). The most recent global analysis (Hinkel et al., 2014) estimates the global costs of protecting the coast with dikes to 2100 are significant with annual investment and maintenance costs of US$ 12–31 billion under RCP2.6 to US$ 27–71 billion under RCP8.5 and the global costs associated with coastal erosion (beach and shore nourishment) at a further US $1.4 to $5.3 billion per year across the low, mid and high A1B scenarios (Hinkel et al., 2013).

Similar types of national I-A studies have been undertaken in a large number of countries (e.g. in Canada, (Stanton et al., 2010): Brazil (Margulis et al., 2010): Guyana (ECLAC, 2011b), the UK (Evans et al., 2004), the US (Neumann et al., 2011), Germany (UBA, 2012) and many more, and there are also similar studies at local level (e.g. in Georgetown in Guyana, Hull in the UK and South Florida in the USA, ECA, 2009, etc.).

These studies find that coastal adaptation is extremely effective, reducing damages significantly at low cost and leaving low residual damages: they therefore report high benefit to cost ratios, which generally increase throughout the 21st century.

The annualised adaptation costs are generally a low proportion of GDP (i.e. often less than 0.1%: Agrawala et al., 2011) though this does vary with country and region.

However, this evidence base predominantly uses the impact-assessment driven methods, and they focus on a limited number of technical responses. Furthermore, these studies - and costs they provide - exclude (Brown et al., 2011) maintenance costs for dikes (though this has been added in the most recent global estimates) and the additional wind storm damage (see later). They assume good levels of existing protection and no existing adaptation deficit, which is a particular problem in developing countries. They omit the costs of adaptation to address impacts associated with salinization (e.g. saltwater intrusion barriers, changing water abstraction sources, or freshwater injection) and port infrastructure and port activities and tourism. Importantly, these costs – and the options considered– do not address coastal or marine ecosystem losses and they do not take account of the effects of enhanced coastal squeeze from hard protection.

Some of these gaps are being addressed. The EACC global study (2010) [for developing countries] estimated adaptation costs for ports assuming a strategy of continuously raising existing port areas as sea levels rise, though the estimates were modest when compared to sea defences (at an annual cost up to 2050, of under $0.5 billion per year for developing countries). More specific studies are emerging on the costs of specific ports, such as the IFC (2011) study in Cartagena, Colombia, in this case using an adaptive management approach.

There is also a growing evidence base on the cost of adaptation against tropical windstorms under climate change and wind damage. This includes studies in the US in Florida (e.g. RMS 2009) which found potentially high adaptation costs for retrofitting of windows, doors and garage doors and especially for roofing upgrades. There has also been studies on adaptation costs and benefits against changing tropical windstorms in the Caribbean (ECA, 2009: CCRIF, 2010) and Samao (WB, 2009).

More recent coastal studies have started to move towards capturing the adaptation challenges outlined earlier in this chapter, and this has a very large influence on the options prioritised, and the costs and benefit estimates.

First, estimates of costs and benefits of adaptation vary with the objectives and the level of protection assumed. Many of the assessments (above) assume modest levels of risk protection, which are below existing protection standards (at least for the dense urban areas of OECD countries). As examples, there are much higher protection standards in some countries (e.g. the Netherlands) or major cities (e.g. London), and adaptation costs will be much higher than the studies above, if these protection levels are maintained (as can be seen from existing coastal flood defence expenditures).

Second, these studies assume foresight, i.e. the model is run for one scenario at a time, thus they do not factor in the costs of addressing uncertainty. Studies that factor in uncertainty usually have higher costs, as decisions move away from the optimum. In addition, studies that analyse more extreme sea level rise, i.e. with projections of 1 metre or more by 2100, report higher damage and adaptation costs (e.g. Vafeidis et al., 2011 globally: Brown et al., 2011 in Europe, using DIVA and Brown et al., 2009 in Africa).

Third, the cost functions used are simplified and reflect basic technical responses. However, individual city-scale protection schemes can have extremely high costs, especially for port – river cities which require more complex engineered structures. As an example, the costs of protecting London to acceptable levels of risk against future sea-level rise may require an additional barrier and supporting works towards the end of this century (under high SLR scenarios), which could cost £6 to 7 billion alone (EA, 2009: 2011). At the global level, there are many such major urban cities, which have high asset values that justify high protection levels. Hallegatte et al., 2013, analysed 136 global coastal cities and report indicative adaptation costs of US$350 million per year per city, or approximately US$50 billion per year for the 136-city sample.

Finally, earlier studies assume highly effective adaptation, and ignore the costs of policy implementation. A comparison of recent national and local planning assessments in the OECD against the modelled evidence base above (Watkiss et al., 2014), indicates that adaptation costs are likely to be higher in practice than the earlier evidence suggest. This is particularly the case when there are higher standards of acceptable levels of risk, uncertainty and more extreme SLR scenarios are included, or there are lower levels of existing protection (higher adaptation deficits). As an example, the estimated annual costs for future flood protection and flood-risk management to climate change in the Netherlands (alone) has been estimated to be in excess of €1 billion per year (Delta Commissie 2008: Delta Programme 2014) with similar annual costs also estimated for the UK (Foresight, 2004: EA 2008: 2011). These are many times higher than the I-A studies for the same countries (e.g. see Brown et al., 2011).

Outside of the OECD, a particular issue is around existing protection levels, especially in major cities, and it is clear that there are high costs involved in raising resilience to address existing risks, though this raises difficult issues around whether these costs should be attributed to climate change.

The evidence shows a recent shift towards more practical coastal adaptation, i.e. focusing on what to do now and in the short-term (with long-term perspectives in mind), not just the long-term future, and to the consideration of uncertainty, e.g. towards iterative approaches. It also includes a wider set of soft or non-technical options, many of which build on existing good practice. These include early warning systems, natural coastal protection systems or natural offshore engineering (in OECD countries), coastal buffer zones such as mangroves (e.g. in developing countries), and a greater focus on integrated and sustainable policies within integrated coastal-zone management. Many of the early options identified in these studies focus on low- or no-regret options, rather than engineered coastal protection, see Box

A number of different early low-regret options have emerged, many of which draw on existing disaster risk management or coastal protection good practice measures. There are existing economic studies of many of these options, which provide information on costs and benefits, and emerging studies of how the benefits of these increase under climate change, though the transfer to the future context does involve some differences (as the past is no longer a good predictor of the future). More details are provided in the ECONADAPT policy document supporting this book, building on earlier review work from Mechler (2012) and Watkiss et al. (2014). As examples, promising options include:

• Climate services, forecasting and early warning systems (EWS, for evacuation or preparation) for tropical storms. These have high benefit to cost ratios (World Bank, 2011). Specific studies include enhanced climate services for hurricane risk in the US for household and the oil and gas industry (Lazo et al., 2010: Lazo and Waldman, 2011; Considine et al., 2004), and in developing countries (in Bangladesh (Paul, 2009) and South-East Asia (Subbiah et al., 2008), where they have particular high benefits in reducing deaths and injuries. The benefits increase under climate change, because of the higher storm surges with sea-level rise, and the potential changes in storm intensity and frequency (ECA, 2009).

• Disaster risk management and emergency/contingency plans (emergency infrastructure including shelters and rescue centres, responses actions, preparation for flooding), forums/institutional strengthening and awareness raising have been shown to have high benefits: costs, indeed these have been found to be among the highest of all early actions for current risks and future climate change (e.g. Cartwright et al., 2013 in Durban).

• Alternatives to hard protection in the form of natural coastal buffer zones (mangrove conservation, replanting and restoration), as well as shoreline restoration, seagrass restoration and marine and coastal protection (including corals). These ecosystem based adaptation measures have high environmental benefits, and often provide enhanced livelihood benefits in developing countries. They are often recommended as priority options with the highest BC ratios (e.g. mangrove and reef restoration to combat hurricane risk under current and future climate change, as in ECA, 2009 in Samoa and CCRIF, 2010, in the Caribbean: mangrove planting for protection against typhoons in Vietnam, IFRC, 2002). However, in high income countries, the costs of mangrove restoration can be very high (e.g. as in the USA as reported by World Bank, 2011) and as identified by Watkiss et al. (2014), there are often policy costs involved, notably around enforcement and protection to ensure the benefits of these schemes are maintained, though these can be reduced through community based schemes.

• Risk transfer including insurance, reserve funds and risk pools/facilities (IPCC, 2012: CCRIF, 2010). These include a variety of mechanisms for risk transfer, and are particularly important for low probability, high-consequence events (Mechler, 2012).

While these early low-regret options have immediate benefits – and provide enhanced resilience for the future – on their own, they may not be sufficient to address risks (see World Bank, 2011). Complementing these are a set of responses that start to build resilience to longer-term change, though these tend to involve more site specificity and thus the low-regret characteristic of these options varies. As examples:

What are low- and no-regret adaptation options?

Numerous studies (UKCIP, 2006; Watkiss and Hunt, 2011; Ranger and Garbett-Shiels, 2012; IPCC SREX, 2012) have recommended that no- and low-regret actions are a starting point for adaptation, as they have the potential to offer benefits now and lay the foundation for building future resilience. No-regret adaptation is defined (by the IPCC) as adaptation policies, plans or options that 'generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs'. This often focuses on options that address the current adaptation deficit (e.g. disaster risk management), options that are more efficient and generate cost savings (e.g. improving irrigation efficiency) or options that address existing problems (e.g. reducing post-harvest losses), though many of these are actually development options.

However, there is no agreed definition of low-regret options, and definitions vary. These include:
• Options that are no-regret in nature, but have opportunity or transaction costs;
• Options that have benefits (or co-benefits) that are difficult to monetise (e.g. capacity building, non-market);
• Low cost measures that can provide high benefits if future climate change emerges; and
• Options that are robust or flexible, and thus help with future uncertainty.

In this context, a pragmatic definition of low-regret is used - that focuses on promising early adaptation options. This includes options that are effective in addressing the current adaptation deficit, but also future-orientated, low-cost options that build resilience, flexibility or robustness, as well as capacity building and the benefits it provides through the value of information.

Source DFID, 2014.

• Climate risk screening, siting and design of major infrastructure has been found to have high benefit: cost ratio or high cost-effectiveness if included at the design stage (e.g. ADB in the Micronesia/Cook islands (ADB, 2005), because of the avoided reconstruction costs from floods and storms. The siting of critical infrastructure such as hospitals, water treatment, etc. away from high risk areas is a low regret option, and some over-design to offer higher protection levels is often justified, because of their importance post-disaster (World Bank, 2011).

• Land-use planning and set-back zones. A further option is to use risk mapping to consider current and future risks. Some studies report that coastal zoning/back away has high BCRs for hurricane protection (currently and increasing under climate change) and is ranked highly among all options considered (e.g. CCRIF, 2010 in the Caribbean: ECA, 2009 in Samoa), and revising coastal set back lines can have high benefit:cost ratios in other areas (Cartwright, 2013 in Durban). However, in middle income and OECD countries, set-back zones do run into high opportunity costs of land.

• Building codes. While building codes are often cited as a potential low-regret option to address future challenges (IPCC, 2012), the picture is more complex. In the US, very high building codes can be justified because of the high value of property, which in turn leads to positive benefit to cost ratios, which will increase further with climate change (e.g. in Florida, ECA, 2009). The World Bank (EACC, 2010) for Samao investigated increased wind resilience in building and infrastructure design from 1 in 10 to 1 in 50 year event, with a forward look with climate change, and found high benefits (that exceeded costs). However, CCRIF, 2010 (in the Caribbean) found that building codes (for wind) had low benefit: cost ratios in some countries and only modest ratios in others.

Hochrainer--Stigler et al. (2010) considered the improvement and retrofitting of residential structures in highly exposed developing countries to hurricane risk (St Lucia) and also found modest benefits. This implies greater site-specificity, i.e. the justification will vary with the risk level (high wind speeds (tropical storms and building damage) and/or storm surge (flooding) and potential benefits, the marginal costs of higher resilience, the existing cost and life-time of the asset, noting the shorter life-times/lower costs in developing countries, the costs of retrofitting based on local costs of materials and labour, and on the discount rate. Again there are policy costs involved, including guidance and especially enforcement, which need to be factored in.

There has also been more focus on alternatives to engineered coastal defences in OECD countries. There are studies that assess the costs and benefits of spatial planning options (de Bruin et al., 2013). There is also an increasing focus on soft or ecosystem-based (green) protection (e.g. sand dunes, offshore sand banks, and sand engines, as well as managed retreat and coastal wetlands). These have advantages, especially in offering co-benefits and flexibility against uncertainty, but assumptions are critical for costs and benefits. De Bruin (2012) looked at sea level rise in the Netherlands and compared a non-technical option (sand dunes) against hard structural protection, with an analysis of decision trees and future options including flexibility: while the soft schemes offered greater flexibility and lower capital costs, maintenance costs were higher, thus ranking of schemes is influenced by discount rate.

There are studies of other ecological alternatives, such as salt marshes: a cost-benefit study of the latter in the Netherlands (Rijkswaterstaat Waterdienst, 2011) reports these eco-variants are less expensive than traditional options over the longer term (net present value) and in terms of construction costs, but they are more expensive in terms of management and maintenance costs alone. This includes alternative flood management strategies, e.g. in New York (Aerts et al., 2013: Aerts et al., 2014), which compared the costs of large-scale flood protection, wetland restoration and buffer zones and increased building codes for future climate change as well as other long-term challenges. The initial investment costs of alternative strategies varied between $11.6 and $23.8 billion, maximally, though a hybrid solution, combining protection of critical infrastructure and resilience measures that can be upgraded over time, was found to be less expensive. However, with increasing risk in the future, storm surge barriers may become cost-effective, as they can provide protection to the largest areas in both New York and New Jersey.

Finally, a number of OECD countries have moved to full adaptive management, looking at the overall adaptation pathway – from short-term responses to long-term analysis. In the Netherlands the Delta programme has advanced short-term measures that increase adaptability (flexibility) and resistance to extreme events (robustness), to make it possible to delay reaching tipping points, and most recently (Delta Programme, 2014) moved to dynamic adaptation pathways, and most recently has used dynamic cost-benefit analysis (Kind, 2014: Eijgenraam et al., 2014). Similarly, the Thames Estuary 2100 project (TE2100) ((EA, 2009; 2011) used an iterative approach to consider future protection responses to London, built around an iterative portfolio of options linked to enhanced coastal monitoring.

Complementing this, there have been a number of studies that have started to apply the new support tools on decision making under uncertainty to coastal adaptation (see Chapter 6 for a discussion of these tools). Many of these have used real options analysis, due to the high capital investments and the nature of single, directionally bounded, gradual change for sea level. A simplified example of the approach is included in the UK supplementary guidance on adaptation (HMT, 2009) but there are examples that have applied these in more practical applications.

Van der Pol et al. (2015) looked at dike heightening in the Netherlands with ROA. Scandizzo (2011) applied ROA to assess the value of hard infrastructure, restoration of mangroves and coastal zone management options in Mexico, concluding ROA highlights the value of gradual and modular options. Kontogianni et al. (2013) used ROA to assess the value of maintaining flexibility (e.g. scaling up or down, deferral, acceleration or abandonment) to engineered structures in Greece. Linquiti and Vonortas (2012) analysed coastal protection investments and found using real options led to better use of resources in Dhaka and Dar-es-Salaam. There are, however, also examples of robust decision making, with a study of planning coastal resilience for Louisiana (Groves and Sharon, 2013).

In summary, the coastal sector remains a highly advanced sector, and it is the one area where practical examples of iterative adaptive management are emerging most rapidly. It is also proving to be a test area for new decision support approaches, and the identification of low- and no-regret options. This is providing new insights, and allows some validation between spatial scales, and over time from older to new studies. A general finding is that more policy orientated studies, in OECD countries at least, are indicating higher costs than the previous modelling literature. This is due to the consideration of uncertainty, and the higher costs (engineered structures, opportunity, transaction and policy implementation costs) associated with major structures. For developing countries, the same message is similar, but is compounded by the issue of the adaptation deficit, thus there is a greater focus emerging on low-cost or no-regret options that offer coastal resilience and other benefits.

Flooding and water management

Climate change is projected to disrupt global and regional water cycles, though these changes will not be uniform, with differences between wet and dry seasons and between seasons (IPCC, 2013), arising from changes in precipitation, temperature and evapo-transpiration, snow recharge and glacier melt, etc.

This is likely to intensify a number of potential risks, including more frequent and/or intense floods, and changes to the water supply-demand balance including potential water deficits and water quality (IPCC, 2014a). While these changes to the hydrological cycle and water management are closely related, they are separated in two classes of risks in the review below.

River, Surface Water and Urban Flooding Risks

Projections of future climate change (Field et al., 2012: IPCC, 2013) suggest extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century. Where future rainfall intensity increases, or where heavy rainfall events become more frequent, this has the potential to increase flood risks, either related to river floods or surface water floods (flash floods) (Kundzewicz et al., 2014). These lead to a number of potential impacts, which include (Bubeck et al., 2011) tangible direct damage or physical damage to buildings, intangible impacts that arise in non-market sectors (such as fatalities, ecosystem damage), indirect damage to the economy (Koks et al., 2013), such as disruption to transport or electricity supply, and indirect intangible losses, such as subsequent disease outbreak or mental health impacts.

However, the analysis of flood related damages – and adaptation costs and benefits – is more challenging, because of the probabilistic nature of extremes (Ward et al., 2014) and the very high site-specificity (Wagenaar et al., 2015). Similar to coastal systems, river flood damage is affected by the level of protection assumed, information on existing protection levels is sparse (Hall, 2014). Because of this, methods have been devised to derive likely levels of flood protection (e.g., Jongman et al., 2014; Mokrech et al., 2015).

At the global level, the EACC (World Bank, 2010) study looked at the costs of water supply and flood protection adaptation together, reporting costs of adaptation \$14.4 to 19.7 billion per year in the period 2010- 2050 for developing countries. Around one third of these costs were due to river flood adaptation costs. The analysis used a global hydrological model and an I-A approach, assessing the costs of maintaining acceptable flood protection levels, with differentiated levels between urban and rural levels. Flood protection was assumed to be provided through a system of dikes and polders, at a cost of \$50,000 per square kilometre in urban areas and \$8,000 per square kilometre in agricultural areas.

Annual operation and maintenance costs were assumed to be 0.5 percent% of construction costs. Ongoing research (Ward et al., 2015) is advancing quantitative estimates of the costs (and benefits) of adapting to increased riverine flood risk using the GLOFRIS modelling cascade, at the global level.

At the regional, national and local scale, it is possible to run more detailed hydrological models, linking these to probability-loss damage functions, which capture the impacts of events of different return periods. These can be integrated into a probabilistic annual damage, andoften consider protection against acceptable risk, i.e. the costs to maintain protection against a 1 in 100 year event under future climate change, though some examples of CBA exist, in which reductions in future damage (with climate change) are compared to additional adaptation costs. These types of studies draw on existing information on the costs (and effectiveness) of existing flood protection schemes, e.g. which have been collated in Europe (HKV and RPA, 2014) and in the USA (see MMC, 2005). For a recent review of the methodologies applied to this type of risk assessment, and for an outlook to future research directions, see de Moel et al. (2015).

An example, using the European wide LISFLOOD model, the estimated economic benefits (the reduction in damage costs) of maintaining levels of river flood protection across Europe (to a minimum of a 1 in 100 level) under future climate change were €8 billion/year by the 2020s, €19 billion/year by the 2050s and €50 billion/year by the 2080s (A1B, EU27, undiscounted), though a wide range was found from different climate projections (Rojas et al., 2013). Estimates of the potential costs of delivering this adaptation led to the conclusion that benefits would outweigh costs, and the study noted that due to the large residual damage costs at this very low level of protection, a higher protection level would likely be optimal. Ongoing work in the ENHANCE project is looking at the potential financial stress due to increasing flood risk in the EU (e.g. Jongman et al., 2014). This indicates that due to increasing risks, incentives for risk reduction are needed, and adaptation can reduce risks at positive benefit to cost ratios in many regions.

There are similar studies at the national and river-basin level in many countries as well, i.e. in the Netherlands (Van Ierland et al., 2007: Delta Committee, 2008; Bouwer et al., 2010) in the UK (Evans et al., 2004: Defra, 2012: Penning-Rowsell et al., 2012), in China (Foresight, 2012), Nepal (IDS, 2014). There are also studies of how insurance protection might be negatively affected by increased exposure (Jongman et al., 2014), an additional form of existing (and future) adaptation.

Such studies show that adaptation has potentially large benefits in reducing flood related damages under climate change. However, in many cases the scale of investment is large, as these studies tend to focus on protection i.e. flood defence measures which are capital intensive and have high maintenance costs. A similar finding is reached with investment and financial flow studies, which look at the likely increases needed for adaptation on top of existing flood defence budgets, and find high costs, especially where there are strong increases in risks levels, e.g. in Bangladesh (UNDP, 2010) and Nepal (IDS, 2014).

However, while these studies provide useful information, they are subject to the same challenges as identified for coastal I-A studies, and the challenge of uncertainty is usually much greater. As a result, the discipline of flood management adaptation is moving in a similar direction, towards a focus on early low-regret options to address existing extremes (IPCC, 2012) – which is closely aligning to the disaster risk reduction/management area - and also considering uncertainty.

There is reasonable information on the costs and benefits of early low regret options, as this can draw on the existing DRR literature. Mechler et al. (2014) undertook a systematic review of the costs and benefits of flood risk management appraisals (ex-ante) and evaluations (ex-post), analysing 27 studies. The study demonstrates that investing in risk management can pay in many contexts and for many interventions and hazards and concluded that, if risk was properly (probabilistically) taken into account in the assessments, an average benefit to cost ratio was close to 5 to 1 for flood related risks. This review was expanded and details are provided in Watkiss et al. (2014) and in the ECONADAPT assessment. Options with high benefit to cost ratios include:

• Enhanced meteorological and hydrological information, forecasting and the use in early warning systems for river floods have been shown to have high benefits (e.g. in the US EASPE, 2002: MMC, 2005; Europe, IDRS, 2008: Desbartes, 2012: World Bank, 2011.; and for developing countries, World Bank, 2012).

• Disaster risk management and emergency/contingency and preparation response plans (such as sand-bags, mobile structures, evacuation, etc.), forums/institutional strengthening and awareness raising have also been shown to have high benefits: costs (Hawley et al., 2012).

• Creating the enabling environment for adaptation, including routine monitoring, flood forecasting, data exchange, institutional reform, bridging organizations, contingency planning for disasters, insurance and legal incentives to reduce vulnerability (Wilby and Keenan, 2012), which are 'low regret' but are not cost-free.

• Enhanced maintenance regimes for drainage and sewage systems, i.e. clearance of existing channels (e.g. Moench et al., 2009; ECA, 2009: Ranger et al., 2011) (or in LDC context, the introduction of drainage) are another low-regret options.

• Risk transfer including insurance, reserve funds and risk pools/facilities, especially for more extreme events (see Jongman et al., 2014 for an analysis in Europe).

• There are a number of household level adaptation responses that can either reduce risks or reduce damages and there has been analysis of the cost-effectiveness of these in the UK (ASC, 2011). Simple household level options also exist in developing countries (e.g. Moench et al., 2009: World Bank, 2012).

• Additional low regret options include integrated water resource management (e.g. Mechler, 2005) and climate smart agriculture, covered in later sections.

Many of the most promising options are 'behavioural' or soft measures – information and education, preparedness, forecasts and warning systems, emergency responses (see Hawley et al., 2012). There is evidence to suggest that the benefits of these 'soft' options increases significantly under higher climate change (e.g. Moench et al., 2009; Risk to Resilience, 2009 in India, Nepal: ECA, 2009) though the level depends on future risk increases and timing/discounting, and on their own, they may not be sufficient to address all risks (World Bank, 2011).

Mecher et al. (2014) identify a number of key assumptions and methodological challenges in such studies. One important finding was that indirect and intangibles impacts make a large difference to results, but are often not accounted for. When included, such additional benefits may positively or negatively impact results. For example, Kull et al. (2013) evaluated the historical performance of physical flood protection of the Rohini river in Northern India. While this ex-post evaluation initially led to positive net benefits, when making the analysis more realistic by considering intangible effects, the assessment became inefficient.

Mechler et al. (2014) also highlights that recent thinking has also identified a shift away from infrastructure based hard resilience to preparedness and systemic interventions, with a much greater focus on soft resilience, noting these are much more difficult to assess using CBA. Community based interventions are also stressed in studies that analyse costs and benefits of current and future adaptation to floods in developing countries (e.g. Moench et al., 2009). Kirshen et al. (2006) in Boston reports that softer measures were more cost-effective than hard measures.

More recently, there has also been a focus on ecosystem based (green) and spatial options as an alternative to river engineering. This include watershed management (enhanced conservation and restoration, notably of upstream catchments with forests), natural flood plain management, including water flow regulation and controlled flooding, natural protection structures (e.g. as an alternative to concrete), and sustainable urban water management (i.e. urban drainage) to reduce urban flood risks. It also includes spatial options that move beyond engineered control, such as the 'room for the river' strategy in the Netherlands.

There has been a review of green schemes in Europe (HKV and RPA, 2014), where they are a priority in European adaptation policy. This identifies some cost-benefit studies of existing ecosystem based (green) schemes. In the Netherlands (Rijkswaterstaat Waterdienst, 2011) considered 2 freshwater sites and found ecological variants of flood defences (e.g. reed-land) were less expensive over the longer term (net present value) and in terms of construction costs, but more expensive in terms of management and maintenance costs alone. There are also assessments of wetland restoration in Stockholm (Kettunen, 2011), flood storage in the Humber estuary in the UK, with benefits in avoiding upstream defences (EA, 2009c) and for the Elba in Germany (Teichmann and Berghöfer, 2010: TEEB DE 2014). Economic analysis on these options - in the context of climate change - was also undertaken in the UK (Frontier, 2013b).

However, it is worth noting that benefits are often delivered in the future, due to the time for full ecosystem establishment and services (Naumann et al., 2011).

There has been less analysis of intra-urban flooding, though some of the country level studies above (notably for the UK (Evans et al., 2004) and Germany (UBA, 2012)) include adaptation costs. This is also becoming an area of interest with examples at the city scale. Desjarlais (2011) performed a cost-effectiveness analysis of urban water drainage in Montreal, examining the impact of different rainfall return (2 and 10 year return rainfall) on the performance of the stormwater network over 50 years.

More practically, Copenhagen has developed and undertaken a cost-benefit analysis for a cloudburst plan, which is likely to get implemented through water charges (City of Copenhagen, 2012). The plan, estimated to cost DKK 3.8 billion, identifies measures that will both make the city greener and keep it blue by diverting the water over ground when possible. Recognising that all initiatives under the Plan cannot be implemented at the same time, priorities have been identified based on: areas at high risk, initiatives that are easy to implement, areas where other related initiatives are underway, and areas where there is scope for synergies

These studies do indicate that the costs retrofitting wastewater and storm-water infrastructure to cope with higher flows under climate change can be extremely high, and this area warrants further empirical studies and analysis. There are also some cost-benefit studies of sustainable urban drainage systems (RH DHV, 2012).

There are also a set of responses that start to build resilience to longer-term change, as well as having immediate benefits. Commonly cited option to address current and future risks from climate change is the use of risk screening for new infrastructure, to take account of future climate risks in siting or design. This can include land-use planning, critical infrastructure siting and building codes. As for the discussion of similar options in the coastal domain, these options can have high benefit: cost ratio or high cost-effectiveness if included at the design stage, but there are greater issue of transferability and there are often high opportunity, transaction or policy implementation costs.

Finally, for longer-term challenges a number of OECD countries have moved to adaptive management, looking at the overall adaptation pathway – from short-term responses to long-term analysis. In the Netherlands the Delta programme has included consideration of river flooding (Delta Programme, 2014) moved to dynamic adaptation pathways (see also Haasnoot et al., 2013) and most recently to dynamic CBA for river and coastal protection (Kind, 2014; Eijgenraam et al., 2014). There have also been a number of studies that have started to apply the new support tools on decision making under uncertainty to adaptation. This includes the consideration of real option analysis to water and flood risk infrastructure in an urban site in the UK (Gersonius et al., 2013) and housing design for flooding in Mekong Delta Vietnam (Dobes, 2010), as well as robust decision making to flood risk management in Ho Chi Minh City in Vietnam (Lempert et al., 2013: Dahm et al., 2014).

Water supply and management risks

Water supply and wastewater services are vulnerable to climate change impacts (Loftus et al., 2011). As well risks to water resources (and deficits) across multiple sectors, there are risks to water infrastructure and water quality, as well as activities that depend on water (e.g. hydro-power, river transport, power station cooling). However, while the contrast in precipitation between wet and dry regions and between wet and dry seasons is projected to increase (IPCC, 2013) there will be regional exceptions and the projections are uncertain, making adaptation challenging.

Adaptation to reduced water availability is often presented in terms of management of supply and demand. Supply measures include increasing water storage capacity (e.g. dam construction, increase dam storage capacity, off-stream reservoirs for agriculture, rainwater harvesting, artificial wetlands, off stream polders); water distribution improvement (e.g. leakage control, meters installation, dual water systems); greywater reuse and rainwater harvesting; desalination; water transfer; aquifer storage and recovery; and water shipment. Demand measures involve increasing water use efficiency and reducing water consumption through changed sectoral activity (e.g. relocation of industrial production), behavioural changes, and technological uptake (e.g. water efficient appliances).

Adaptation of wastewater and storm-water infrastructure includes more frequent capital investments and maintenance schedules and resilient infrastructure design. It also includes separation of wastewater and storm water networks and the use of sustainable urban drainage systems. Poorer influent water quality and reduced dilution effects may result respectively in greater treatment costs to reach current water quality standards respectively for drinking water and wastewater discharge. The use of ecosystem-based measures to deal with droughts, flood risks and worsening water quality for example through river restoration, rural land use change and establishing or protecting wetlands has also been proposed.

Early reviews (OECD, 2008) found few studies on costs and benefits of adaptation for the water sector, although this has increased. These vary from single sector studies to cross-sectoral demand assessments, and can capture a range of costs and benefits, including non-market values.

At the global level, the UNFCCC (2007) based on Kirshen (2007) estimated additional investment and financial flow of $9-11 billion per year in 2030 to deal with changes in the availability of water supply. The World Bank project "Economics of Adaptation to Climate Change" (World Bank, 2009; Ward et al., 2010) estimated adaptation costs for developing countries from 2010 to 2050 using a global hydrological model, estimating costs for municipal and industrial water supply (2005 prices, no discounting) of US$ 10 billion (wettest scenario) and US$11 (driest scenario) based on the cost of restoring future water demand using simple cost functions (I-A).

There are also water supply adaptation costs at the regional level. Assuming that adaptation focuses on engineering options, Hughes et al. (2010) estimate adaptation costs (capital and operating costs) at about 1–2% of baseline costs for all OECD countries, or about $5.5 billion per year. Including the use of economic incentives to affect patterns of water use produced a net saving of about $7.6 billion per year for all OECD countries.

The ClimWaterAdapt project applied a multi-criteria evaluation of adaptation measures in Europe, identifying river restoration, improving irrigation efficiency and water retention as the highest ranked measures (Flörke et al., 2011). In contrast, adaptation of dykes, desalination and water transfer warranted careful attention as their unintended consequences.

Muller (2007) estimated the annual costs of adapting existing and building new climate-proofed urban water infrastructure in (sub-Saharan) Africa at US$ 2-5 billion. AfDB (2011) and Doczi and Ross (2014) review other estimate for Africa. Bárcena et al. (2010) estimate adaptation costs for Central America to ensure the supply of water for household, residential and agricultural consumption, reporting these are 1.2% to 5.4 of (2008) GDP depending on discount rate and climate future, though costs primarily arise late in the century.

There are now also a larger number of studies at national level. In the OECD, an early national study of the costs of adaptation options was carried out for the Netherlands by Van Ierland and colleagues (Van Ierland et al., 2006; De Bruin et al., 2009b). This estimated that climate-proofing the water system would cost €19 billion, improving river capacity €7 billion, relocating fresh water intake points 50 to 100 million Euros, increasing water storage and retention in or near city €3.3 billion Euros, creating water storage on farmland €15 to 50 million, and upgrading sewer systems €3 to 5 billion. The study used a simple combination of qualitative, participatory-based multi-criteria analysis to prioritise adaptation options, followed by a CBA. Authors note the difficulty to get detailed economic information on each option, meaning that the study did not quantify the costs of many options, and did not quantify benefits and non-monetary values.

ICF International (2007) also carried out an early assessment of the potential costs for upgrading wastewater networks in England and Wales. The study calculates the incremental costs of treatment in sewerage works to achieve water quality parameters assuming more frequent low flows in rivers. Calculations only consider BOD, and use cost function (including capital and operating costs) for quantity removed. The study examined incremental costs under two hydrological scenarios and two regulatory scenarios. Incremental annual costs range between GBP 4 million for 20% flow scenario and GBP 10 million under 50% flow scenario. The unit cost increase with application of WFD standards and with more severe climate change impacts (50%) as more stringent abatement requirements will become more expensive in unit cost terms.

Tanaka et al. (2006) used an integrated water supply model in California, considering supply management (e.g. building reservoirs, groundwater recharge, water transfers and waste water reuse), changes in water systems operation (e.g. seasonal variations in management, conjunctive use, groundwater banking, improved reservoir operation), changes in water allocation rules (e.g. market mechanisms, changes in water rights and pricing), and improvement of water use efficiency. This highlights the importance of socio-economic driven water demand as well as climate change, noting they are of the same order, and that while adaptation is possible, it could be costly.

Bank of Greece (2011) used a cross-sectoral general equilibrium (CGE) model and applied to adaptation in the water sector (as well as other sectors), looking at network loss reduction and estimating adaptation cost of €68 million a year by 2100 (discounted at 2%), compared to benefits (in avoided damage) of €380 million a year. Adaptation in the water sector is associated with reducing losses in network from 60% loss to 10% implemented between 2025 and 2050 and between 2050 and 2070. The model considers that investment costs represent additional public expenditures, and therefore applies an adjusted interest rate. Using the same CGE model, Faust et al. (2012) assessed adaptation costs and benefits in Switzerland, taking account of adaptive capacity and looking at water prices. Modelling of adaptive capacity is based on the elasticity of substitution for inputs to sectoral use. Results show that, regarding impacts, water prices may vary significantly depending on climate change, but global economic impact for Switzerland remains small as price of water is currently very low. Regarding adaptation, results show the importance of building capacities to reduce water losses and transform production processes in the long term. Most uncertainty comes from climate scenarios and not from the choice of various elasticities.

Metroeconomica (2006) in SE England and SE Scotland, estimated adaptation costs for anticipated water deficits up to 2100, using indicative cost-yield curves and cost-effectiveness analysis. The annual cost of eliminating most water deficits for each region between 2006-2080was estimated at GBP 6-39 million, while the annual cost of climate change impacts for the same period without adaptation was estimated at GBP 41 - 388 million. The ASC (2011) also developed household water adaptation cost curves for the UK.

Sussman et al. (2014) has collated national and regional estimates for adapting water infrastructure, including estimates for water treatment, which indicates potentially high investment costs.

Skourtos et al. (2013) developed a cost database of adaptation options in Europe that included technologies for water saving. Results suggest that the integration of cross-sectoral effects significantly alters the ranking of the adaptation measures, while the results of uncertainty analysis were characterised by significant variation.

Fewer studies have examined costs and benefits at river basin level. For example, Martin-Ortega et al. (2012) used CEA complemented with disproportionality analysis to design cost effective adaptation and mitigation strategies for phosphorous reduction from agriculture and sewage treatment works to comply with the WFD and Habitats Directives. They tested the approach for the Tame sub-catchment of the Thames catchment. Costs for agricultural measures represent the whole farm costs for fertiliser reduction. The study also included foregone benefits from agriculture into the costs of implementation. The most cost effective combination of measures found was establishing ten meter width riparian buffer strips, a 20% P fertiliser reduction for all crop lands, adoption of minimum tillage systems, and establishment of constructed wetlands and winter cover crops.

Studies also exist on water management at the “local” scale, i.e. for a municipality or a project. An early study by Dore and Burton (2001) examined in Toronto, Canada, the costs of adaptation options such as building new treatment plants, improved efficiency of actual plants or increases in retention tanks. The study found that costs could be as high as CAD 9.4 billion.

Kirshen et al. (2004) assessed, in Boston, the costs of extra treatment of wastewater to reduce input of nutrient in the river and the establishment of wetlands and infiltration basins, finding that climate change and population growth may lead to US$ 30-39 million in capital cost and US$ 0.3–0.6 million in annual operating costs.

Anderson (2008) examined the economic benefits of water reuse in Sydney through cost functions added to a stochastic analysis of future projected water supply and demand (20 to 50 years). Economic benefits were evaluated by way of reduced (avoided) investment and operating costs for drought contingency works and loss of utility cost to consumers of water restrictions during droughts by implementing water reuse or other new supply measures. Mánez and Cerdà (2014) used a cost-benefit analysis to prioritise adaptation measures in water supply and sanitation in Valencia and Catalonia. The study ranks adaptation measures not only against NPV, but also initial investment, private costs, environmental external benefits, environmental external costs, and social external costs.

In the developing country context, there have also been several studies, which have used different approaches. One set of studies has been based on I-A analysis, and use hydrological and water management models at river basin levels to consider cross-sectoral demand as well as supply. Examples include SEI (2009) in Kenya and World Bank (EACC, 2010) in Ethiopia. These consider standard water management options, e.g. in Kenya the analysis looked at the costs and benefits of demand management including efficiency in irrigation and urban water use; supply management including reservoirs and groundwater use; ecosystem protection including erosion control and rainfed agriculture: finding demand side measure were always beneficial, but supply side and ecosystem options depended on the future climate projections. The work of Callaway et al. (2006) in the Berg river basin in South Africa is remarkable for providing estimates of establishing an efficient water market. The study is methodological comprehensive as it differentiates development and adaptation costs and benefits, and uses an optimisation hydrologic-economic model modified to take climate change into account. The study found that establishing an efficient water market, with or without new water storage capacity resulted in the highest net returns.

An alternative set of studies looks at investment and financial flow analysis, looking at the potential increases under scenarios of climate change to 2030 (UNDP, 2011). Six countries (Costa Rica, Dominican Republic, The Gambia, Bangladesh, Honduras, Peru) included the water sector in their analysis, though costs varied significantly between the countries (e.g. the total costs to 2030 were estimated at $2 billion in Costa Rica, but over an order of magnitude higher than this in Bangladesh. However, these early costs include some development options (i.e. associated with the adaptation deficit) though they have less focus on uncertainty.

The NEEDS project (UNFCCC, 2010) also estimated water adaptation costs based on financing needs in two countries, Jordan and the Maldives, with adaptation costs estimated at US$1.5 billion and $44 million respectively. The difference is due to the inclusion of large engineering projects such as dams and water transfers in the former.

Kirshen et al. (2005) considered the future water balance in the Huang Ho River in China and the costs of additional storage and groundwater development to maintain target yields using simple cost functions. The study reports annualised incremental costs of US$ 500 million over a 50 year period at 3% discount rate.

Vergara et al. (2007) estimated the costs of water diversion and infrastructure development in response to melting glaciers in Quito, Ecuador, and found that the incremental net present value of accelerated investments required for the next 20 years to US$ 100 million representing a 30% increase compared to the no climate change scenario. Dhakal and Dixit (2013) used a participatory approach to evaluate monetary and non-monetary costs and benefits of for managing the Rupa lake watershed in Nepal under climate change. The study also prepared a detailed analysis of how costs and benefits could be shared (i.e. community, private, local government, international).

IIED’s stakeholder-focused cost-benefit analysis was developed for developing contexts where data gaps and distributional issues are important (Lunduka et al, 2012). A range of techniques were included: individual interviews, consultation workshops to develop criteria for ranking, and focus group discussions to discuss collectively costs and benefits. The approach first started with a CBA followed by separating costs and benefits to different stakeholders. Dhakal and Dixit (2013), Lunduka (2013) and Mohamed (2013) used this approach to evaluate monetary and non-monetary costs and benefits for managing, respectively, the Rupa lake watershed in Nepal, Lake Chilwa catchment in Malawi, and changing from surface to drip irrigation systems in the Tadla region in Marocco. In Nepal, Dhakal and Dixit (2013) evaluated willingness-to-pay and how costs and benefits could be shared (i.e. community, private sector, local government, international community). Mohamed (2013) found for example that conversion from flood to drip irrigation could improve farm-level net returns and public net benefits. In addition, NPV of drip irrigation for small-scale farmers could be improved if the technology was extended to include food crops rather than limiting it to cash crops. Lunduka (2013) found win-win for the local farming and fishing community if soil and water conservation techniques complemented irrigation and rain-fed agriculture.

Alongside these studies, there are a number of additional studies look at specific water impacts.

• There are several studies on the costs of adaptation for the hydro-electricity sector, in terms of electricity system planning (using demand and energy optimisation models) as well as individual options for plants. Examples include studies in Brazil (Margulis et al., 2011), Ethiopia (World Bank, 2010) and Nepal (IDS, 2014). These indicate potentially large costs, from the additional capacity needed to address demand shortfalls, though the outcomes vary significantly with climate projections.

• There are also some studies of the costs of adaptation in relation to the abstraction temperature of river water for cooling for thermal and nuclear power plants, an issue that emerged in the 2003 European heat wave, with estimates these at European scale (Mima et al., 2011: CEPS/ZEW, 2010) and in some countries (e.g. UBA, 2012 in Germany).

• Finally, there are also a set of impacts that look at river transport, which is important on the major river systems of Europe. This includes analysis of the costs of adaptation along the Rhine (Jonkeren, 2009) and other major river navigation routes (ECONET, 2014).

These examples highlight a growing literature on the economics of water sector adaptation. However, caution is needed in as there are widely varying methods, cost metrics and benefit categories used, different discount rates, as well as varying temporal and spatial scales, and there are issue of the transferability of results given the high site-specificity.

The results depend on whether analysis is undertaken from a cross-sectoral perspective, and take account of future socio-economic as well as climate change. They also depend on whether studies focus only on supply options, or also assess demand (including behavioural and economic measures), and also on the water system itself, i.e. whether public run, whether water pricing is in place, etc. What is clear is that in countries exposed to high risks, adaptation costs could be high, especially when supply side investment is needed.

At the same time, there has been a greater focus on low-regret options for water. These include:

• Early options that increase knowledge and awareness (de Bruin et al., 2009b), such as enhanced climate and hydrological monitoring and information (Flörke et al., 2011) or metering (Darch et al., 2011).

• Options that help deal with current climate variability, such as water efficiency measures (Flörke et al., 2011; Lunduka et al, 2012), leakage reduction (Darch et al., 2011) or reclaimed water (Mánez and Cerdà, 2014).

• Options that help improve watershed management such as integrated water resource management (de Bruin et al., 2009b) changing water allocation systems (Nkomo, 2006), ecosystem based adaptation, river restoration and water retention measures (de Bruin et al., 2009; Flörke et al., 2011

• Options that deal with the "adaptation deficit, i.e. support development needs (UNFCCC, 2010; Lunduka et al, 2012; Doczi and Ross, 2014). Dyszynski et al. (2010) for example identify building capacity and increasing social protection through disaster risk management, both of which helps with existing and future risks.

There is also consideration of decision making under uncertainty, notably with studies that use robust decision making, i.e. to identify options that perform well over many futures scenarios, rather than optimally, and real options analysis.

• Lempert and Groves (2010) for example applied (RDM) to develop the management plan for water and wastewater utility in Southern California. The study compared the current plan and an adaptive management approach, identifying and costing low regret options such as increasing groundwater storage, water recycling, and monitoring the region's supply and demand balance.

• More recent applications of RDM include the application to water scarcity in the Colorado River Basin (Groves et al., 2013) and Nassopoulos et al. (2013) to dam dimensioning for a small catchment in Greece. A simpler application of RDM – considering climate uncertainty only – was applied in the South of the UK (Hulme and Dessai, 2008).

• Jeuland and Whittington (2013) applied Real-Option Analysis to water investment planning on the Blue Nile in order to identify optimal operating decisions for a series of large dams. It explores the trade-offs between larger and smaller dams and their location including their sequencing in space and time, and identifies flexible strategies in design.

• Darch et al. (2011) assessed the effects of long term climate uncertainty on water investment planning in London and look to identify robust options for supply and demand and develop decision pathways (iterative risk management).

Other risks to infrastructure

While heavy precipitation and flood related damage are key risks to infrastructure, there are other climate related risks. These include heavy precipitation and heat related damage, notably for infrastructure, i.e. where climate change leads to exposure that is outside the design range.

This includes transport infrastructure (road and rail) where heat related damage is important. It also includes storm-related damage (excluding tropical storms, which were covered earlier) and issues with freeze-thaw cycles and permafrost melt. Early studies such as Burton and Dore in Canada (2001) focused on these costs of adaptation of the road network (roads, bridges, storm water management systems), and water utilities (drinking water treatment plants, and wastewater treatment plants).

More recently there have been global, national and local studies. At the global level, earlier studies used investment and financial flow analysis to estimate the adaptation 'mark up' to anticipated future infrastructure. This led to high infrastructure costs, especially in OECD countries as report in UNFCCC (2007). Subsequently The EACC (World Bank, 2010) used I-A method uses dose-response functions for construction costs and captured adjustments in building standards to enable assets to withstand predicted changes in climate conditions, with maintenance costs for existing assets (for changing average temperature and precipitation). Standards were assumed to be forward looking, were adjusted to withstand changes for 50 years from the date of construction. It reports infrastructure costs [for developing countries] of $13.5 – 27 billion per year in the period 2010- 2050, with the wetter scenario leading to higher adaptation costs. Urban infrastructure—drainage, public buildings, and similar assets—accounts for about 54 percent of the infrastructure adaptation costs, followed by railways at 18 percent, and roads (mainly paved) at 16 percent.

In the transport sector, there are some cost estimates of the additional cost of adaptation for transport infrastructure at country level, including road and rail (Jochem and Schade 2009: SCCV, 2007 in Sweden: UBA, 2012 in Germany, which include cost-benefit assessments). Recent studies in the UK indicate many of these risks can be addressed at low cost as part of planned maintenance and refurbishment regimes (Atkins, 2013) though higher costs are associated with strengthening bridges vulnerable to climate change under alternative future climates (see Wright et al. (2012) in the US) and in localised hot-spots where landslips are a risk and site strengthening and maintenance costs are high (e.g.in Austria). There have

also been costs on road infrastructure in developing countries, including the EACC country studies (e.g. in Ethiopia and Ghana, WB, 2010).

There are a number of studies that have investigated the risks to infrastructure This includes Larsen et al. (2008) in Alaska, which indicates climate change could increase infrastructure costs by as much as 10–20%; in present value terms ($3.9 billion to $6.6 billion for the period 2006–2030) and Zhou et al. (2007) in the Northwest of Canada.

A number of studies have considered the potential costs of adaptation to non-tropical windstorms, including Hunt (2012) in Europe, UBA (2012) in Germany and SCCV (2007) in Sweden. These indicate potentially high absolute costs, though good benefit: cost ratios (at least for some options). However, a key issue is that the influence of climate change on these events remains uncertain, in relation to the change in intensity and severity and the likely position of storm tracts.

While the retrofitting of infrastructure (to higher design standards) is often expensive, there is opportunity to introduce resilience as part of design, including flexibility in infrastructure design as well, to allow easier upgrades as part of future maintenance and refurbishment cycles, though this flexibility tends to have a cost. However, while it is possible to simply over-design infrastructure to address future risks, this has a cost penalty, which may not be justified given the timing (and uncertainty) of future benefits, as well as the (economic) lifetime of investments. In the developing country context, over-design has the potential to divert key sources of finance away from options that give greater short-term economic benefits (e.g. for rural road development projects, it may be better to spend resources to maximise the length of roads built and maintained, than to spend these resources on a small number of highly resilience roads, especially noting these only have a design lifetime or around a decade).

Therefore, low-regret options are likely to focus on simple siting (avoiding high risk locations) and low-cost over-design). The one exception to this is in relation to critical infrastructure (water supply, and health and emergency), especially where there is a long life-time, especially where this is important in reducing risks post-disaster.

Risks to Agriculture

Agriculture is a highly climate sensitive sector and climate change has the potential to lead to major effects. While the issue of water availability is critical, linking to the earlier section, there is a much wider set of risks. This is based on many potential climate variables, which can impact directly and indirectly on crop production, agricultural supply and value chains. They involve potentially negative effects (e.g. from lower rainfall and/or increasing variability) but also potentially positive effects (e.g. from CO_2 fertilization and from extended growing seasons), as well as complex changes from the changing risks of extreme events, the range and prevalence of pests and disease, etc. These lead, in turn, to changes in production and thus trade. These are also potential effects from climate change on horticulture, viniculture, industrial crops and livestock, and on the multi-functionality role of agriculture. There are also important impacts on individual livelihoods, e.g. from subsistence farmers up to national economies: in the most extreme cases, there are potential risks to food security and the breakdown of food systems (IPCC, 2014a), possibly leading to socially contingent effects.

The patterns of potential impacts of climate change on agriculture vary across time and location. For temperature increases of 2°C, negative impacts on yield are projected for major crops in tropical and temperate regions (without adaptation), although individual locations may benefit (IPCC, 2014a): below this, in the period to 2050, the projected impacts vary significantly across crops and regions, including net potential yield gains as well as losses, and with the level of adaptation (though for low-latitude tropical regions, negative yield effects tend to arise at moderate temperature increases (Rosenzweig et al. 2014)).

Adaptation options at the farm level include earlier sowing dates, which can stabilize yield levels by avoiding later summer drought and high temperature stress [Garrido, et al., 2011; Siebert and Ewert, 2012]. Planting new varieties can increase climate resilience [Hauggaard-Nielsen and Jensen, 2001], as can intercropping two or more crops [Hauggaard-Nielsen and Jensen, 2001]. Minimum tillage technologies can offer benefits including decreased soil loss, and increased soil organic carbon [Rosenzweig and Tubiello, 2007; Smith and Olesen, 2010].

Crop residue retention in fields can improve soil structure (i.e. reducing erosion risk and increasing water holding capacity), improve long term fertility and nutrient use efficiencies as soil organic carbon increases [Yamoah, et al., 2002], and increase crop water availability. Landscape diversification, different crop types in rotations, different crop varieties, and the use of non-crop species in cropped fields can suppress pests and/or disease (Lin [2011]). Multiple cropping has also proven to be beneficial as an adaptation option to climate change [Nendel, et al., 2014; Waha, et al., 2013a]. Improving the water productivity of crops is also key to improving yields in rainfed environments with various soil water conservation techniques able to limit evaporation [Rockström and Barron, 2007]. Higher water productivity in irrigated systems can result from more efficient application techniques, new varieties, manipulation of crop physiological responses, and improved scheduling to match plant growth[Morison, et al., 2008].

On the economic side, the main adaptation options include trade, shifting crop types and land-use expansion. International linkages through trade and commodity prices can have a major influence on the effectiveness of adaptation planning through a strong influence on the profitability of agricultural production.

The previous OECD review (2008) identified that agriculture was fairly well covered in relation to the benefits of adaptation, but much less so on the costs. It identified a good coverage of adaptation benefits for agriculture, with two sets of studies. The first relates to many studies of autonomous (farm-driven) adaptation using crop models and impact-assessment (e.g. Parry et al., 2004). These generally consider the increased use of irrigation and fertiliser to address failing yields (sometimes complemented with autonomous market adaptation in relation to trade). The results can be used as part of, or as an input to, global economic models, taking account of the total impact of climate change rather than just the direct domestic impacts. The second uses econometric (Ricardian) assessments analysis (e.g. Seo et al., 2009; Kurukulasuriya & Mendelsohn, 2009) to assess the relationship between climatic factors and land value or farm net revenues. These studies consider autonomous (farm-driven) adaptation, which in the case of crop models, was primarily focused on increased use of irrigation and fertiliser (and sometimes other crop management or crop switching) to address failing yields under climate change, complemented with autonomous market adaptation in relation to trade (when global models are used).

At the global level, the earlier UNFCCC (2007) study (McCarl, 2007) used in IFF methodology estimated adaptation costs (research, extension and irrigation) at $14 billion/yr globally in 2030, of which 50% was in developing countries.

Following this, IFPRI (2009) – supporting the global EACC World Bank Study - assessed the potential global costs [in developing countries] of adaptation in the agricultural sector using a global agricultural supply-and-demand projection model (IMPACT) linked to a biophysical crop model (DSSAT) and estimated agricultural productivity investments and adaptation costs (in the period 2010-2050) at US$7.1–7.3 billion [for developing countries]. The EACC summary (World Bank, 2010) provided an updated global estimate of US$2.5–3 billion [for developing countries]. The study reported that while there were significantly lower crop yields and production (especially for irrigated and rainfed wheat and irrigated rice) under climate change, costs were low, because welfare was restored through trade, rather than yield, though this implies some regions will become big food importers. Such studies – which include global trade - highlight the need to take account of the overall climate change impact on the amount of food available, rather than just direct domestic impacts (e.g. Shrestha et al, 2013).

These results are similar to a broader literature at global, regional and nation level that reports high economic benefits from agricultural adaptation, though as highlighted by the IPCC (2014d) [Porter et al.] while agronomic adaptation improves yields, the effectiveness is highly variable, and differs for crops and regions.

A similar set of studies has been undertaken in national studies. The World Bank EACC country studies (World Bank, 2010b, c, d, e, f, g) (in Bangladesh, Bolivia, Ethiopia, Ghana, Mozambique, Samoa, and Vietnam) all considered agriculture. These primarily used crop models, but provided new insights through the consideration of uncertainty, and the linkage to economy wide models, with adaptation provided through research and irrigation. As an example, the country study in Ethiopia (World Bank, 2010e) estimated high baseline costs of climate change (especially on rain-fed irrigation) and found that adaptation could reduce welfare losses by around 50% (thus there are still residual damage). The costs of adaptation and the residual impacts (together) for this one country alone were estimated to be $1.2 billion to $5.8 billion per year (2010 – 2050), though the study highlights different options could reduce these costs.

There have also been agricultural sector investment and financial flow studies – to explore early adaptation costs. National level agriculture adaptation costs to 2030 were estimated in the UNDP IFF initiative (UNDEP, 2011) for Bangladesh, Colombia, Ecuador, Gambia, Liberia, Namibia, Niger, Paraguay, Peru, Togo, Turkmenistan and Uruguay. The adaptation costs for agriculture in these 12 country UNDP IFF assessments totalled $3 billion/year in 2020 rising to $6 billion/year in 2030, though a high proportion of these costs were in Bangladesh. The total costs are high when compared to the earlier global estimates. This can be explained partly by the different methods, assumptions and coverage. The IFF studies are better grounded in current policy and they include a much greater coverage of risks as they look to build resilience across all existing policy areas. They also have a more realistic assessment of current costs and therefore the realistic costs of delivering additional adaptation (including implementation and policy costs, and the costs to the private as well as the public sector). However, they include some costs for action that are targeted at reducing the existing adaptation deficit, they are often focused on irrigation options, and they exclude the potential for international trade.

There are a large number of other country studies. In India (TERI, 2010) the estimated costs of adaptation to 2050 were estimated at $1.4 billion per year (similar to the EACC estimate for South Asia). The analysis in Brazil (Margulis et al., 2010) estimated adaptation costs, identifying genetic modification as this had a higher benefit:cost ratio than irrigation, requiring R$1 billion a year in research investment.

However, these modelling studies have a number of critical assumptions. They have optimistic assumptions about trade (and trade levels in relation to domestic food security objectives). Studies that report very low adaptation costs generally assume very high levels of trade – and imply huge changes in levels of imports in some countries, ignoring the costs that would be borne by local farmers as part of this transition, as well as the externalities associated with lower food security levels. It is highlighted that the assumptions in such studies – and the omission of key cost categories – would not be accepted by the countries affected.

They also have little consideration of constraints and wider cross-sectoral issues. Studies that include these in (e.g. Iglesias et al., 2012 for Europe), either due to competition for water, or from environmental limits on fertiliser use, find current policy constraints would reduce adaptation levels and/or increase adaptation costs. Similarly, Ricardian studies tend to overestimate benefits and underestimate costs.

Critically, these studies do not consider uncertainty, considering scenarios one at a time, and assume capacity and foresight at farm level. The crop modelling studies highlighted above show that assumptions of future yields under climate change vary very significantly with projections. They also vary with critical assumptions of impact, such as assumed CO2 fertilization or crop responses, a fact highlighted by the recent Inter-Sectoral Impact Model Inter-comparison Project for agriculture, (Rosenzweig et al., 2013). Finally, they tend to work with a very narrow set of options, notably irrigation and fertiliser use, which lend themselves to the modelling environment.

As a result, more recent studies have shifted to the consideration of more immediate and practical adaptation, and started to consider uncertainty. Much of this has focused on addressing current climate variability, i.e. with no- and low-regret options, and the option of climate smart agriculture (FAO, 2013). These are forms of sustainable agricultural land management (SALM) practices that improve soil water infiltration and holding capacity, as well as nutrient supply and soil biodiversity. They include options such as agroforestry, soil and water conservation, reduced or zero tillage, and use of cover crops. These reduce current climate related risks from rainfall variability and soil erosion, increase soil organic matter and soil fertility, increasing productivity, and reduce emissions by reducing soil emissions or preventing more emission intensive activities. These contrast with more traditional measures to increase productivity, such as fertiliser use or increased irrigation, which have the potential for negative externalities.

There has been analysis of the costs and benefits of these options, though much of this relates to current practice (noting that under conditions of climate change, benefits should increase).

In the OECD, examples included qualitative benefit:cost assessment (a multi-criteria analysis) for a range of climate smart agriculture initiatives in Canada (British Columbia, 2013). There was also an analysis of the costs and benefits of conservative/low tillage in Germany (UBA, 2012), though this found benefit to cost ratios were low and uncertainty was high (noting it also reported low BCrs for irrigation).

In the developing country context, there has been much more analysis of climate smart options, because of their potential for rain-fed agriculture. They provide immediate productivity benefits, and Branca (2011) provides a dataset on the evidence for these. The costs of these measures have also been reviewed in detail by McCarthy et al. (2011). Specific examples of cost-effectiveness assessment and even cost-benefit analysis also exist (e.g. Branca et al. 2012 in Malawi: ECA, 2009 in Mali), and these studies generally report that these climate smart options are win-win for food security and climate change adaptation, as well as providing mitigation (reduced GHG) benefits. Some options lead to direct co-economic benefits, e.g. agroforestry can generate additional income streams from fuel wood, building material and food. In general, there are high benefit:cost ratios reported for these options and they are often selected as early adaptation priorities, including under future climate change (e.g. ECA, 2009: Lunduka 2013), though for the latter it is usually difficult to quantify the benefits of future resilience against future climate change.

However, McCarthy et al. (2011) highlighted some critical issues about these options. First, there is high variation in costs per hectare between sites, i.e. transferability is important (see also Kato et al. 2009). The estimates for investment and maintenance categories vary widely depending on the specifics of the situation, reflecting the large differences among regions, agro-ecological conditions, pre-project land uses, household asset endowments, and the differences in cost structure of the various types of activities considered. Second, and perhaps more important, many of these climate smart options have important opportunity and transaction costs. These include opportunity costs of labour and land, as well as up-front cash outlays that are a barrier to poor farmers. For example, some options take-up land and thus forego crop income in the short-term. Even if opportunity costs are negative over the longer term horizon, it is important to consider these in the short run as they are certainly an important barrier to adoption, particularly in subsistence

economies or to poor farmers (who generally have the highest opportunity costs). The costs and benefits also vary with assumed discount rate, noting that some options, such as soil improvement or agroforestry, take several years to establish benefits, while costs are borne immediately, thus they are only profitable in the long run (e.g. Tenge, et al. 2007). They therefore do not tend to perform as well under CBA as some conventional measures (e.g. Shiferaw et al. 2001), or require lower discount rates or ancillary benefits to appear more attractive, noting these are not always easy to quantify. In relation to farm uptake, some of the economic benefits are not accrued to local farmers (e.g. economic benefits of lower GHG emissions). Estimating costs is also difficult, especially when markets are not perfect (or informal) and labour is mostly supplied within the household. The bottom line is that promoting and implementing various climate smart techniques is going to be more costly than some of the figures currently cited about in the climate change literature, especially for the poorest producers, who are perhaps the most important to reach.

Alongside this, in developing countries, there has been a focus on other early low- and no-regret options. In OECD countries, there has been work to identify early adaptation options (no- and low-regret), such as the UK (Wreford and Renwick, 2012: Moran et al., 2013). Promising options identified in such studies include increasing water supply through on-farm storage reservoirs and incentivising efficient water management, the introduction of soil conservation measures and increasing expenditures on research and development.

Recent analysis (IPCC, 2014a) reported that some adaptations (e.g., cultivar adaptation and planting date adjustment) were (on average) more effective than others (e.g., irrigation optimization). Crop switching was also found likely to have high benefit to cost ratios in Germany (e.g. UBA, 2012)

There are also studies that look at agriculture and irrigation in areas of water scarcity, as outlined in the earlier section on water supply and management risks. Notably studies include the early work in Australia (Howden et al., 2003), which highlighted the high benefit to cost ratios of R&D to improve the evidence base, and the more recent focus on vulnerable areas such as the Murray–Darling Basin (Adamson et al., 2009; Conor et al., 2009). The latter found that relatively low cost adaptation strategies are available for a moderate reduction in water availability and thus costs of such a reduction are likely to be relatively small. In more severe climate change scenarios greater costs are estimated. Adaptations predicted include a reduction in total area irrigated and investments in efficient irrigation..

A shift away from perennial to annual crops is also predicted as the latter can be managed more profitably when water allocations in some years are very low.

Recent research on increasing summer drought in the Rhine and Meuse river basin because of climate change (Koopmans et al. 2015), suggests that there is a considerable scope for market adaptation (irrigation, change in cropping pattern, international trade) to mitigate economic damage.

There are also now more sophisticated national, regional and global assessments being undertaken, that are considering global food markets, trade and the cost of climate change adaptation (FAO, 2015). These include studies that link crop models and global trade models (e.g. using global, recursively dynamic, and partial equilibrium models, such as GLOBIOM), using the latter to explore climate change impacts and adaptation policies including consumer support policy (e.g. Mosnier et al., 2014, in four Eastern Asian countries). They also give an estimate of global adaptation costs of 12- to 119 billion USD per year in 2050 (for a wet and medium climate change scenario respectively). Such studies highlight that looking only at crop yield projections in one region is inadequate to derive conclusions on climate change impacts and adaptation. More recent studies have also factored in uncertainty and robustness to such global assessments and considered transformational adaptation (e.g. Leclère et al., 2014), including uncertainty with stochastic modelling (Fuss et al., 2011: 2015) to see how this affects strategies and costs, as well as expanding the list of options to include climate smart agriculture.

In developing countries, many of the early low-regret options are effectively agricultural development strategies. While this raises some issues of attribution, there is good evidence that they have high benefit: cost ratios. They include (Ranger and Garbett-Shiels 2012: Watkiss et al., 20140:

• Climate information, agro-meteorological information, seasonal forecasting and early warning. These have high economic benefits for agriculture (see Clements et al., 2013).

• Information systems and networks between farmers, as well as capacity building and awareness raising;

• Research and development;

• Crop switching/planting (agronomic management). altering cultivation and sowing times, crop cultivars and species, and marketing arrangements;

• Crop diversification, farm activity diversification and household income diversification,:

• Pest and disease management, including post-harvest losses.

• Water management (see earlier).

• Ecosystem based adaptation (see later).

• Insurance.

In some countries, these early options have been assessed in terms of additional costs with respect to sector adaptation plans (e.g. Tanzania, GoT, 2014) and there are also some examples of the application of more consideration of addressing uncertainty in early planning (e.g. Downing et al., 2011: Matiya et al., 2011). It is stressed that many of these options are already included in agricultural development programmes, or else the subject of extensive tests or pilots. As an example, the climate resilience plan for agriculture in Ethiopia (Watkiss et al., 2013) identified a substantial overlap between activities currently financed under the Federal MoA budget and the priority 40 adaptation options identified, and further that approximately 63% of the existing MoA budget was spent on resilience-oriented activities (though this included social protection).

These early low-regret options often work best when implemented as combinations, thus there is a focus on portfolios of options (multiple strategies), rather than single, technical solutions. As an example, Di Falco and Veronesi (2012) found that the most promising low-regret options provided largest benefits (i.e. they are most effective in increasing net revenues) when they were implemented as portfolios, rather than on their own. As an example, the positive impact of changing crop is significant when coupled with water conservation strategies or soil conservation strategies.

There is debate is on whether irrigation should be considered an early low- or high regret option. While some studies highlight these options as low regret (e.g. IPCC, 2012) others disagree (e.g. Ranger and Garbett-Shiels, 2011), notably when viewed from the perspective of cross-sectoral water demand and up-front capital costs, and in relation to new investment versus efficiency improvements in existing.

There has also been a move towards more iterative analysis of adaptation. The UK ECR (Frontier, 2013) developed adaptation pathways (roadmaps) for the agricultural sector.

These identify early options that focus on building the enabling environment and information for adaptation in the farming sector, i.e. they move away from the technical optimisation of early studies towards research, awareness, information provision, best practice and addressing barriers.

An iterative management approach was also used in the Ethiopian Climate Resilience Strategy (Watkiss et al., 2014). Interestingly, while the early focus was on low- and no-regret options, and early preparation for long-term change, the adaptation costs were still significant, estimated at $240 million per year by 2020 and more than $500m per year by 2030 (public) and rising to $300m year in 2020 and $600m per year by 2030 when the private sector was included. However, the iterative approach highlighted that under conditions of high future change (e.g. high warming scenarios or early negative impacts on crops), costs post 2020 would rise more quickly, as portfolio options would need to be brought on stream quicker. Importantly, the analysis identified some areas of long-term risk that warranted early action (i.e. now), notably for coffee, due to the longer crop cycles and the long time-scale for changes in cultivar or areas.

The main disadvantage of these iterative approaches for agriculture is the difficulty in identifying risk thresholds, which is challenging due to the combination of many climatic parameters, multiple impact risks (with different thresholds), and complex socio-economic and institutional baselines. These problems are compounded with scale and geographical aggregation ad application can also be challenging due to the dependencies between options within a pathway.

The agricultural sector has not had so much of a focus on decision making under uncertainty, probably because of the lower levels of large capital infrastructure, though there is an application of real options analysis to agricultural irrigation in Mexico (World Bank, 2009) as well as the iterative risk application highlighted above. Dyszynski and Takama (2010) applied RDM to micro-insurance in Ethiopia.

The evidence base on adaptation costs and benefits for horticulture, viniculture, livestock, forestry and fisheries (aquaculture) is less developed (though Howden et al, give a review), though some studies are emerging, for example in relation to forestry management and fire control (e.g. Price et al., 2012; Khabarov et al., 2014) and viniculture (Zhu et al., 2013), both of which are priority areas for early adaptation given the long life-cycles for production.

Heat-Related Extremes – Health, Energy and the Built Environment

Over the 21st century, there will be an increase in hot temperature extremes due to climate change, as global mean temperatures increase, and it is very likely that heat waves will occur with a higher frequency and duration (IPCC, 2013). These will lead to additional health impacts in the form of mortality and morbidity, though there will also be some potential benefits from reductions in cold related mortality and morbidity. Higher temperatures – both average and heat extremes – will also affect building comfort and energy demand for heating and cooling.

Previous reviews have assessed these two aspects from individual sectoral perspectives. However, while the adaptation response can involve some sector specific responses (e.g. heat alert systems), co-ordinated responses are likely to needed to address these risks, e.g. which span both public health and the built environment. These are therefore considered together below, rather than as two separate domains.

Health adaptation

The increase in the frequency and intensity of temperature extremes will lead to direct impacts on thermal stresses (cardiovascular and respiratory diseases) and indirect impacts through urban air pollution which can exacerbate preceding health conditions. The impacts of heat waves are expected to affect the most vulnerable groups in the population such as the elderly, children, people in poor health and economically disadvantaged groups.

There are estimates of the impacts and economic costs of heat related mortality in Europe (e.g. Kovats et al., 2011; Watkiss and Hunt, 2012) and other countries. These report potentially high welfare costs, though the size varies with the valuation metric used.

An early low-regret option to address current and future risks from heat related mortality is through the use of heat alert systems ((Heat Health Watch Warning System, HHWWS). These systems are set up to advise the population during heat waves and may include reactive measures such as the identification of vulnerable groups and effective response (financial and domiciliary assistance services, accompaniment to emergency medical services, emergency plans), besides the common preventive actions related to temperature forecasting and dissemination of warnings. The HHWWS is usually launched when a certain critical temperature is reached, above which the temperature is expected to produce significant impacts on human health.

There is ex post data on the costs of these schemes, e.g. in France (ONERC, 2009) which assessed the costs of the French National Heatwave Plan and across Europe (WHO, 2009). The estimated costs of these scheme is cited from under €1 million to up to around €10 million per scheme, depending on the cost categories included, with upper estimates including costs of additional medical personal and/or resource costs (WHO, 2009). As well as the heat warning system, these may include public information and awareness and use of social care networks.

The IPCC (2014e./Smith, et al.) reviewed studies of the effectiveness of heat wave early warning systems, reporting that most studies found fewer deaths during heat waves after implementation. The benefits of such schemes are found to be considerably larger than the costs. As an example, Ebi et al (2004) estimated the benefits of HHWWS at around 468 million€ compared to a cost of the system of around 210,000$ over three years (1995-1998). In Carraro and Sgobbi (2008) the benefits of adopting the HHWWS in Rome after the 2003 heatwaves have been estimated around 134 million€ for one summer. Fouillet et al (2008) compared observed and expected deaths in 2006 heat wave in France and estimated that the implementation of the system saved around 4400 deaths. These indicate that such systems are a low cost response for addressing early heat related mortality. It is highlighted, however, that the existing studies on heat warning systems have been carried out for specific urban areas and are difficult to scale-up to wider geographical scales.

The future annual costs of heat alert schemes are projected to rise as the systems are triggered more frequently with climate change, though the benefits will also increase. Both Ebi (2004) for Philadelphia and Hunt & Watkiss (2010) for London demonstrate that under plausible climate scenarios the cost-benefit ratio is very high, as did the UBA (2012) study in Germany.

However, there are still residual deaths. With climate change, additional adaptation to address heat-related mortality is therefore likely to be needed. As an example, Michelon et al., (2005) report that immediately following the summer 2003 heatwave, €150 million was invested for additional staff and cool rooms in elderly residential homes in France. There have also been cost-benefit assessments of cooling in hospitals (UBA, 2012). These responses – and others that are suggested around the build environment and spatial planning involve intervention from outside public health, discussed below.

Built environment (energy demand)

Temperature is one of the major drivers of current energy demand. Climate change will affect future energy demand, increasing summer cooling (electricity) but reducing winter heating (gas, oil, electricity). These responses are largely autonomous, and can be considered as an impact or an adaptation, but they are strongly influenced by socio-economic drivers (.e. population, household size, building design, efficiency) and energy/mitigation policy.

Both globally and in regions and countries, there are quantitative impact-assessment studies of the likely change in heating and cooling demand (usually from analysis of heating and cooling degree days and energy models). The IPCC (2014b) reports that rising incomes will lead to growing energy demand for cooling even without climate change in warm developing countries/regions, whereas in warm developed countries, rising demand will be driven by higher temperature.

Irrespective of the change in net global energy demand, it is clear that there will be strong distributional impacts to the additional impacts / adaptation costs associated with cooling. Isaac and van Vuuren (2009) conclude that the strong increase in energy related cooling demand occurs in Asia, Sivak (2009) report that of the 50 largest cities, almost 4/5th are in warm developing countries, and very large increases are projected for India (Akpinar-Ferrand and Singh, 2010).

There are now more studies that provide autonomous adaptation costs for these changes. Mima et al. (2011) assessed these costs for Europe, the US, China and India using a least cost-optimisation energy model (i.e. looking at the additional marginal costs of providing extra generation). These indicate large cooling costs, In Europe alone, these were estimated at around €30 billion/year in EU27 by 2050, rising to €109 billion/year by 2100 (current values, undiscounted, for a A1B scenario), though these are largely offset by falling heating demand -though again a strong distributional pattern emerges, with high net increases in Southern Europe. The analysis also considered the additional (discounted) purchases of air conditioning units, which were found to be significant. The costs of air conditioning demand in India was much higher, at $480 billion/year (undiscounted) in India by 2100 (corresponding to 0.27% of projected GDP).

both heating and cooling costs (e.g. Defra (2011) in the UK) (Ackerman and Stanton (2008) in the US) or in warmer countries increased costs of cooling (e.g. Zachariadis, 2010 in Cyprus and Pilli-Sihlova et al. (2010) in Spain).

Where multiple studies exist – e.g. for a single country – these show wide ranges. Sussman et al. 2014 report on five national studies in the US, reporting the three more recent estimates range from $6 billion to $87 billion/year, with higher estimates reflecting the time period and scenario. Estimates vary depending on whether heating and cooling costs are presented in net terms, and according to assumptions about capital expenditure.

All of these studies are highly influenced by the energy models used, the comparison of future socio-economic drivers, and assumptions, including on future energy prices (with or without mitigation). However, none of these studies factor in the health benefits of cooling: air conditioning (AC) reduces the incidence of heat related mortality associated with heat waves (Ostro et al., 2010), which are likely to increase with climate change (a co-benefit).

What is clear is that the autonomous increase in cooling energy is potentially large, especially when they increase peak electricity demand. If this is delivered with increasing AC, this will also have important dis-benefit in the form of higher GHG emissions, conflicting with mitigation (unless electricity is decarbonised). .

More recent literature has therefore focused on planned adaptation. There have also been studies at Member State and local level which have assessed the costs of passive options (e.g. van Ierland et al., 2006; Arup, 2008: ASC, 2011: Mima et al., 2011). This includes a range of options such simple shading and orientation, design and building codes, low- and very low-energy consumption buildings. While these are primarily for new building, some also consider retrofitting of existing houses. While these have the potential to be low regret, these assessments find the benefits vary strongly across the range of climate projections, and with the assumptions on capital costs versus operating savings.

A general finding is that it is more expensive to retrofit. However, these planned responses involve major barriers to implementation (see Neufeld et al., 2010), due to higher up-front capital costs and institutional barriers, for example, passive technologies need to be built at the design phase by one actor (the construction firm) to generate benefits for another (the household owner). This example highlights that autonomous reactive adaptation is unlikely to lead to complementary mitigation-adaptation linkages on its own, and that synergistic policy will need to overcome barriers, requiring planned public adaptation to create the enabling environment, relevant legislation or market signals.

There are also set of broader adaptation options that are associated with spatial planning, e.g. green spaces, more open plan development. These options involve much wider costs and benefits and are more difficult to assess, including potential trade-offs with mitigation (i.e. which seeks less carbon through high density cities, which increases potential heat-island effects). What is clear is that the costs of these policies may be very large, because of the costs of land/opportunity costs of land-use change.

An additional trend in the literature relates to the growing recognition that populations face multiple risks that may better be addressed collectively. For example, a study by Pohl et. al. (2014) analysed the changes to the built environment in a part of Rotterdam, Netherlands, that could be considered, given the expectation that in future decades there will be a range of risks associated with heat, storm water flooding and drought. A short list of measures were evaluated using cost benefit analysis, including (amongst others): adjusting behaviour through better health advice and increased GP knowledge of risks; greening the local environment (trees, small vegetation); insulation of buildings, and; green roofs. The results show that adjusting behaviour through better health advice and increased GP knowledge of risks is one of the five (out of nine) measures that have a positive benefit-cost ratio – a central ratio being of 50 to 1. The study also outlines which stakeholder groups are likely to bear which adaptation costs thereby giving a first indication of the likely ease of implementation.

There have also been a number of studies on green roofs (van Ierland et al., 2006 in the Netherlands, LCCP 2009 in London, UBA, 2012 in Düsseldorf, and Nurmi et al. (2013) in Finland), which have been assessed in terms of co-benefits (e.g. reduced energy, stormwater management, sewer overflow, air quality, urban heat island, greenhouse gases), though benefit:cost ratio appear modest.

Other health risks

There are a large number of other potential health impacts that could arise from climate change, directly or indirectly, including water, food and vector-borne disease, deaths, injuries and mental well-being from extreme events, and effects from altered agricultural production and food insecurity, stress, conflict, etc. There are also risks to health infrastructure and to occupational health. While some of these were captured in earlier sections, a number of them have been considered in the adaptation literature, building from the low evidence base in this area identified in the 2008 review.

There are two global studies that provide estimates of health adaptation costs are (UNFCCC, 2007, also in Ebi, 2008), and World Bank, 2010). Ebi (2008) estimated the costs of adaptation to diarrhoeal disease, malnutrition and malaria by multiplying the number of additional cases of these health impacts from climate change by a unit prevention cost, under alternative non-mitigation climate scenarios, with population kept at 2000 levels. For 2030, a global cost of $5 billion/year by 2030 was estimated, within a range of $3 to 18 billion/year, primarily in developing countries. However, Markandya and Chaibai (2009) note that the study only included operational costs and did not include capital costs needed to establish the health care infrastructure. Parry et al. (2009) highlighted that these health adaptation costs were significant underestimates, as they only included 30-50% of extra disease burden from climate change in developing countries.

The World Bank (World Bank, 2009) used a similar approach to Ebi, applying preventative costs to climate scenarios to estimate the costs of adaptation for malaria and diarrhoea for developing countries up to 2050, but adopted a more sophisticated treatment of socio-economic development. It reported global health adaptation costs were a very low proportion of total adaptation costs, at only $1.5 to 2 billion/year globally, with most of these in Africa. The estimated costs to developing countries in Central and Eastern Europe were very low ($0.1 billion/year in short-term only). The lower costs were due to rapid declines in the baseline incidence of these diseases due to development, as well as updated functions and unit costs. However, the study did acknowledge the costs of adaptation in other sectors that would affect health (the cost of reducing additional cases of malnutrition (agriculture); and the adaptation cost related to extreme weather (floods and droughts)) and the omission of infectious diseases such as dengue, heat stress, population displacement, and increased pollution and aeroallergen levels.

A general finding is that it is more expensive to retrofit. However, these planned responses involve major barriers to implementation (see Neufeld et al., 2010), due to higher up-front capital costs and institutional barriers, for example, passive technologies need to be built at the design phase by one actor (the construction firm) to generate benefits for another (the household owner). This example highlights that autonomous reactive adaptation is unlikely to lead to complementary mitigation-adaptation linkages on its own, and that synergistic policy will need to overcome barriers, requiring planned public adaptation to create the enabling environment, relevant legislation or market signals.

These sets of global estimates have been complemented by a further series of studies in developing countries that have estimated the cost-effectiveness of health interventions to meet near-term targets such as the Millenium Development Goals. These studies provide, nevertheless, useful estimates of the cost of health interventions outside the climate change context as they focus on climate-related health outcomes.

An example of this is the study by Morel et al. (2005) who estimated the costs of meeting health MDGs through malaria control programmes in two sub-Saharan African regions: Southern and Eastern Africa and Western Africa. Various prevention and treatment measures were evaluated over a 10 year period. Preventative interventions included e.g. insecticide treatment of bed nets, indoor residual spraying and treatment of pregnant women whilst treatment measures included distribution of drugs, Annual costs were $468 million for Western Africa and $442 million for Southern and Eastern Africa, though as with the global studies, some relevant costs such as on infrastructure, staff training, monitoring and evaluation are not included. Another example is Kiszewski et al. (2007) who estimated the cost of preventive and treatment measures to decrease the impact of malaria in Africa, Asia and Middle East, and South America, with results comparable to those of Ebi (2008).

A number of other studies have looked at health adaptation costs. India (Chiabai et al, 2010) reports adaptation costs for malaria, diarrhoea and malnutrition under different scenarios of development are in the range $171 -546 million (no mitigation) and $141-445 million for a 550 ppm stabilisation scenario. These estimates are lower than the earlier EACC 2009 study. SEI (2009) estimated adaptation costs for increased malaria, due to altitudinal shifts in the disease, and used prevention costs to estimate future adaptation costs from climate change. ECA (2009) undertook a cost-effectiveness analysis of adaptation options to address cholera and other infectious diseases in Tanzania. In Paraguay, the UNDP (2011) investment and financial flow assessment was applied to health, estimating costs of $150 million in total to 2030. In Ghana, the UNFCCC NEEDS study (2011) also estimated the incremental cost of adaptation in the health sector to be USD 350 million by 2020 and USD 352 million by 2050.

In Saint Lucia (Caribbean region), ECLAC (2011c) estimated the present value of treatment costs for A2 and B2 IPCC scenarios in the period 2010-2050 (592,000 US$ for cardio-respiratory impacts, 31,000 US$ for malaria, 34,000 US4 for dengue and 3,3 million US$ for gastro-enteritis in A2 scenario, using a discount rate of 1%).

In the near-term the most effective measures to reduce vulnerability are programmes that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (IPCC, 2014e. These have high benefit:cost ratios and there is a considerable literature on these f options that finds high benefit to cost ratios (as an example, see Hunt (2011) for a review of water and sanitation options).

However, some options (e.g. large-scale vaccination programmes, infrastructure, waste water treatment) increase costs significantly. As an example, relatively high costs have been projected in Sweden (SCCV, 2007) to account for the increased infrastructure costs for waste water plans that address water supply contamination to address climate change risks. The cost of increased separation/inactivation of micro-organisms in water treatment plants has been estimated at SEK 1,300 million investment for the period 2011–2040 and the accumulated costs of successively adapting the Swedish water supply to increased risks and new conditions due to climate change during the period 2011–2100 estimated to be at least SEK 5.5 billion for local authority water supplies and SEK 2 billion private water supplies. Similarly, there is some evidence on the cost-effectiveness and cost-benefit analysis of vaccination programmes against tick borne disease (Hsai et al., 2002, Desjeux, Galoisy-Guibal and Colin (2005)) – which reports high cost (though benefits/net benefits depend on background incidence rates, i.e. risk).

Desjeux et al (2005), for example, found a negative benefit of more than 5 million€ for a vaccination program against tick-borne encephalitis in French Troop for the period 2004-2014.

Similarly, there are some studies that look at air pollution related risks with climate change, which report potentially high adaptation costs. Epstein and Mills (2005) focus on medical treatment costs for increased asthma cases resulting from reduced air quality due to climate change in the US. Using treatment costs, they estimate an incremental cost of $4.7 billion to address the additional cases. Liao et al. (2010) estimated an additional $11.9 billion would be needed annually to ensure six regions and five cities in the US meet current ambient air quality standards (designed to protect human health), primarily those for ozone.

A recent tool, developed by the WHO, (WHO, 2013), specifically to aid decision makers in making estimates of adaptation costs provides "health" and "other sectors that affect health". Within the health sector, the indicative list of options is split between general adaptation measures that may be required to reduce the health effects of climate change and those that protect population health against specific climate change-related health risks. In the former group are measures such as strengthening primary health care and public health action, building capacity in the health workforce and strengthening surveillance and early warning for climate-sensitive disease. In the latter group are measures such as heat–health action plans (Heat-related risks for mortality and morbidity) and education on food handling and safety (Changed frequency of waterborne diseases). Under the heading of "other sectors that affect health" are included measures such as transport and energy policies that provide green spaces, agriculture, including land management, forestry and fisheries that is managed so as to protect these resources from extreme weather events (e.g. droughts, floods) and their consequences, and social welfare services that can support low-income households who do not have the financial means to pay for adaptive responses.

While the evidence base has increased, there is still a gap between the range of health-related climate change risks, the wide range of options identified as potentially limiting these risks, and the extent to which these options have been subjected to economic appraisal. Most analysis is focused on options that have easily measurable costs attached. Cost coverage is also not complete: capital costs are often neglected, as are resource costs and policy costs.

Biodiversity and ecosystem services

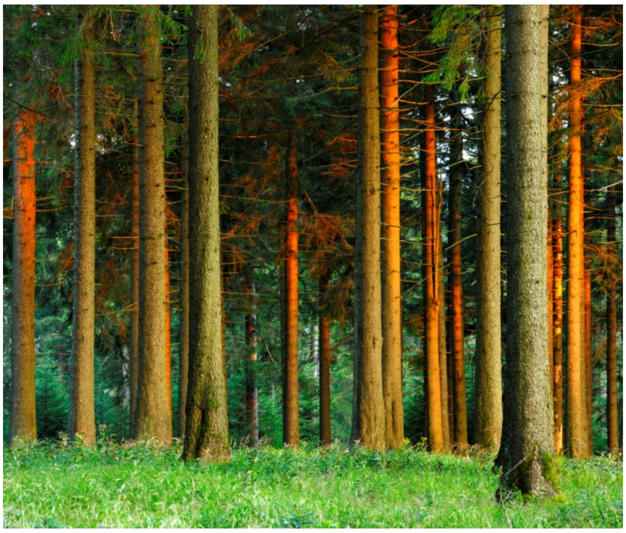
Climate change poses a potentially large set of risks to terrestrial, aquatic and marine biodiversity and the ecosystem services they provide (provisioning, regulating, cultural and supporting services). It will shift geographic ranges, seasonal activities, migration patterns, abundances, and species interactions, and has the potential to increase the rate of species extinction in the second half of the 21st century (Settele et al., 2014).

In terms of adaptation, previous reviews have identified a major gap on costs and benefits in this area, reflecting the challenges involved in estimating impacts. This is a major omission as these are amongst the most vulnerable of all sectors, because of ecological limits and low adaptive capacity. The literature that does exist focuses on the costs of protection and restoration of habitats and species, though there is an increased literature on ecosystem based adaptation ('green' measures) to address climate risks in other areas (see early sections on coastal flooding, water management and agriculture).

There is also more literature on the value of ecosystem services (TEEB, 2009: TEEB 2010) which provides more evidence for economic studies, i.e. for the evaluation of costs and benefits of adaptation measures. The TEEB-Climate Issue (TEEB 2009) highlighted the economic values of restoration projects as an adaptation measure. The biome/ecosystem with the highest benefit-cost ratio was restoration of grassland (75) followed by restoration of tropical forests (37), woodland/shrubland (28) and Mangroves (26), then restoration of lakes/rivers (16), other forests (beside tropical forests, 10), inland wetlands (5), coastal ecosystems (4) and coral reefs (3).

Early low-regret options for adaptation centre on the reinforcement or enlargement of existing measures to protect biodiversity (e.g. use of protected areas, buffer zones, ecological corridors, reducing habitat fragmentation), with some new approaches (e.g. selection of species, translocation of species, management of alien species), and a need for improved information and monitoring.

Earlier studies (Berry, 2007) analysed the global costs of establishing and management of protected areas and the additional expenditure needed for adaptation as part of the UNFCCC IFF (2007) study, estimating additional costs of US$ 36-65 billion per year by 2030, noting the costs would be much higher (about US$ 290 bn) when extended to conserve biodiversity in the wider matrix of landscapes. If the costs of marine protected areas included, all these figures increase by US $29 billion per year. Parry et al. (2009) built on this study and estimated adaptation costs for worldwide terrestrial and marine protected areas at US$ 65–80 billion per year and supported the higher estimate for including non-protected areas from Berry (2007).



A further group of studies at national level also exist. Berry et al. (2006) estimated impacts of climate change for biodiversity using opportunity costs in form of restoration and re-creation costs in the UK. The estimation of the annual restoration costs are based on the UK Biodiversity Action Plan. The calculated annual restoration costs for 11 habitats are for 2050 in a High-Scenario: £ 2.5 mio., in a Low-Scenario: £ 1.4 mio.

The UNDP IFF study (2011) considered the costs of adaptation in Costa Rica for the biodiversity sector, focusing on conservation of terrestrial and marine ecosystems, conservation of inland aquatic ecosystems, prevention of forest fires, and awareness raising, with estimated costs of $1.3 billion by 2030 i.e. rising from $60 million a year in 2015 to $76 million a year by 2030. There is also an IFF case study on fisheries in Peru (UNDP. 2011) which estimates a total cost of $0.78 billion to 2030 (i.e. approximately $40 million/year).

Van Ierland et al. (2007) estimated the costs of establishing a national ecologic network in the Netherlands, and estimated the additional costs to with climate change impacts were 135 million Euro per year. There are very few studies on other options.

A study in Finland (Tainio et al., 2014) analysed the conservation of grassland butterflies under a changing climate, considering promotion of agri-environmental schemes, species translation and dispersal corridors, using CEA. Results indicate that buffer zones are most cost-effective while cost of translocation was relatively modest compared to dispersal corridors. While these studies show many potential co-benefits, they also identify opportunity or policy costs, e.g. loss of land for buffer zones, policy costs of enforcement.

In Honduras, local authorities in coordination with the National Water Utility and the Ministry of Forestry have defined a water management plan, based on EbA options such as reforestation, transitioning to agroforestry, fire control measures and introducing soil and water conservation measures. This plan is applied to the Guacerique Watershed, one of the main areas providing drinking water to the Honduran capital city Tegucigalpa and its implementation has a cost of US$4.2 million. The expected net economic benefits range from US$23.6 to 91.5, depending on the scenario and discount rates considered.

Cartwright (2013) analysed adaptation measures in a eThekwini, a metropolitan region in South Africa – including the City of Durban. The benefit-cost ratios for the three ecosystem-related measures are all larger than one. The measure Natural capital planning and research (including system conservation planning, estuarine management plan and climate change research) shows a BCR of 6.3 and 10.1 (for different scenarios), Natural capital regulation and acquisition of 1.5 to 2.3 (including e.g. and use management, land acquisition) and Strategic natural capital management of 1.0 to 1.9 (including e.g. Restoration, reforestation and protected area management).

There is also an increased interest in the application of adaptive management to this sector, though to date these applications have not focused on economics. Bölscher et al. (2013) analysed fish stock maintenance under climate change with an adaptation pathway approach, looking at salmon reintroduction in the Rhine. It has also proved challenging to apply the new economic tools for decision making under uncertainty to this area. The only study identified for this analysis is an application of portfolio analysis to investigate genetic material that could be used for the restoration or regeneration of forests under climate change futures (Crowe and Parker, 2008).

The overall conclusion is therefore that the evidence remains low, and the information that does exist is difficult to transfer because of diversity and uniqueness of the natural habitats. The limited studies that exist indicate that aggregate costs could be high, and this remains a priority area for further investigation, but also the early implementation of options.

Business, Services and Industry

One sector that has been poorly covered in the past – and remains so – is the area of business and industry. There are some studies of the costs and benefits of information campaigns and avoiding heat induced productivity reduction (UBA, 2012).

Interestingly some recent studies have started to look at the economic benefits of adaptation, e.g. in relation to goods and services, and employment. This includes studies at the European level (Triple E, 2014), Country level (e.g. BIS, 2013 for the UK) and city (KMatrix, 2014 for London.

The one area that has been partly covered is tourism. Numerous studies have assessed the potential effects of climate change on the tourism sector using a comfort index (Tourist Climatic Index) and cost the changes using tourism expenditure. As an example, Amelung and Moreno (2012) apply such an approach in Europe. The key finding of such studies is a strong re-distribution of tourism (and expenditures) – in this case with southern countries such as Spain, Greece, and Croatia facing negative consequences in summertime as conditions become less favourable to tourism, but with positive effects in northern countries, such as the UK, Ireland, Germany, the Netherlands and Austria. These changes in tourism flows can be seen as an impact or an autonomous adaptation response. There is less literature on planned adaptation responses, though the Dominican Republic undertook an investment and financial flow analysis for tourism and estimated the adaptation costs were $0.7 billion to 2030 (i.e. rising from $16 million a year in 2015 to $57 million by 2030).

There are also several studies that look at winter tourism. For example, OECD (2007) assessed the costs of adaptation in the Alps, and the costs of additional snow machines and increased use to cope with decrease snow reliability in the lower altitudes ski resorts, as well as extending ski areas to higher elevations. There are also some studies of preparing slopes in the German region of Bavaria and adapting with summer tourism (cycling) (UBA, 2012).

Cross-cutting themes

A number of cross-cutting themes have also been considered, in relation to available information on the economics of adaptation.

Adaptive Capacity

Recent studies have highlighted the need to build adaptive capacity and focus on the process of adaptation, as well as delivering adaptation options (Downing, 2012).

Capacity building is a broad term (UKCIP, 2008) that involves: gathering and sharing information, research, collecting and monitoring data, raising awareness, education and training; institutional frameworks, best practice guidance and other institutional and organisational activities. It is often identified as an early priority for adaptation, both in relation to current climate variability and future climate change. However, the non-technical nature makes it difficult to assess costs and benefits. There has been some analysis of the value of information with respect to climate services (Clements, 2013) including in the climate context (Macauley, 2010) but this remains a priority for further investigation.

Cross-sectoral

Cross-sectoral and cross-cutting effects of adaptation measures – and likewise ancillary costs and benefits - are rarely taken into consideration in adaptation costing, but this is becoming increasingly important in moving to implementation. It is also clear that including such effects can cross-sectoral impacts and their integration into cost-effectiveness analysis can significantly affect the ranking of adaptation measures (Skourtos et al.,2013).

Macro-economic

Most of the studies described in this book are sector based assessments, though there are some examples of partial equilibrium analysis (e.g. in agriculture and energy), and a small number of studies that consider wider economic costs (and metrics) using computable general equilibrium models (e.g. such as some of the EACC studies). There is also an IAM literature on the global costs of mitigation and adaptation, described earlier. However, an emerging priority is to understand the national economic costs of adaptation, and the importance on public finances, GDP, employment, investment, etc.

There has been increasing use of CGE models to model market-driven autonomous adaptation in the form of agents' reaction to changes in relative prices. These exercises focus on single climate-change impacts (e.g. Tzigas et al. (1997), Darwin (1999), Ronneberger et al. (2009), Calzadilla et al. (2009); Aaheim et al. (2010), Bosello et al., 2006, Bosello et al., 2011) or on the interactions of multiple impacts (Bigano et al. 2008; Eboli et al. 2010; Bosello et al. 2009; Aheim et al. 2011; Ciscar et al. 2011).

Carraro and Sgobbi (2008) moved to the national level, and assessed the economic value of the impacts of climate change for economic sectors and regions, aggregated to provide a macroeconomic estimate (GDP) using a CGE model, and included autonomous adaptation induced by changes in relative prices and in stocks of natural and economic resources, as well as international trade effects (changes in prices inducing changes in production and demand). A key priority is to extend these assessments to consider planned adaptation. There has been some initial work in this area. BoG (2011) used a general equilibrium model GEM-E3 to estimate the macroeconomic cost of planned adaptation measures in Greece for Scenario A2 and the sectors of water, forests, transport, tourism, the built environment and coastal zones. Adaptation measures over the period 2025-2050 correspond to an annual expenditure of roughly 1.5% of GDP. This subsequently decreases, to 0.9% of GDP during the period 2051-2070 and to 0.1% of GDP during the period beyond 2070.

Furthermore some attempts have been made to extend CGE modelling capacity to capture market-driven autonomous adaptation, and even planned adaptation. This is usually implemented by re-directing resources, e.g. national investment, toward protection activities. One of the most studied is coastal protection. Bosello et al., (2012) used a CGE model to assess the wider economic costs at the country and sectoral level of adaptation and against sea-level rise in Europe.

Limits of adaptation

While it seems very likely that there will be limits for major climate change, and especially tipping elements/ discontinuities, there are also likely to be limits related to individual sector or geographical contexts. It follows that failure to recognise these limits (as is the case in current economic models) will over-estimate the potential for adaptation to substitute for mitigation. A number of potential limits exist. Adger et al. (2007) identified five: physical and ecological limits, technological limits, financial barriers, information and cognitive barriers, and social and cultural barriers. The physical and ecological limits are absolute. The other types are closely related to adaptive capacity. However, the empirical evidence on the limits of adaptation remains extremely low and there is a lack of evidence on the magnitudes of climate change that would represent future adaptation limits. This is important in relation to knowledge about the limits to adaptation, but would also inform the level and timing of mitigation and the need for early mitigation action.

Transformational adaptation

The recent AR5 study (IPCC, 2014) categorises adaptation into incremental adaptation, where the central aim is to maintain the essence and integrity of a system or process at a given scale, and transformational adaptation, which changes the fundamental attributes of a system in response to climate and its effects. There is, as yet, little economic evidence on transformational adaptation, and it is unclear if this relates to non-marginal change, and thus requires a different analysis framework to marginal CBA for example. This is a further priority area for research.

Discussion

Risk coverage

The inventory of studies collated by the ECONADAPT on the costs and benefits of adaptation provides a useful catalogue for analysing the available evidence.

It is clear that the evidence base has progressed in recent years. There are now hundreds of studies, covering a wide range of sectors and risks. This provides a useful picture of the level of evidence, and allows analysis of some policy insights.

The previous OECD review (2008) presented a table to report the coverage of sectors. This revealed good coverage for coastal sectors and agricultural benefits, and a medium coverage of energy and infrastructure costs. This analysis has been updated with the current review, and the results are shown in the Table.

The updated review shows that the evidence base on the costs and benefits of adaptation has evolved significantly since the earlier review, and now extends to water management, floods, agriculture and the built environment, in addition to coastal zones. However, major gaps remain for ecosystems and business/services/industry, and also the cross cutting themes of adaptive capacity, cross-sectoral convergences, macro-economic effects, the limits of adaptation and transformative adaptation. It is also highlighted that for all sectors, the coverage remains partial. Only a sub-set of climate risks are covered, for example, even for coastal zones, most studies focus on protection and beach nourishment and there is lower coverage of adaptation to address coastal ecosystem loss or salt water intrusion.

An analysis of this new literature, as part of this project, has provided some interesting findings.

First, most of the estimates are from the grey literature – only 25% are academic peer review articles. This is partly due to the recent growth in national studies, as well as the recent increase in studies (and the time delay to publication), though this does raise some issues.

Second, following the earlier discussion, there are now two distinct sets of literature. The first group of studies are impact-assessments and focus on technical adaptation. These studies dominate the literature on future (medium to long-term adaptation). However, they do not include analysis of the implications of uncertainty and they omit a number of key cost categories (see below).

The second group of studies align to the new iterative framing and focus either on early low regret-options (to address current climate variability and build resilience) or decision making under uncertainty for the longer-term. These studies often are more policy-orientated, and are focused on delivering information for early practical adaptation planning.

A comparison of the two groups of literature reveals some key differences.

The impact-assessment studies are stylized and assume highly effective adaptation. The analysis of options is undertaken for defined future scenarios with foresight – one-at-a-time - and this omits the consideration (and costs) of uncertainty, and often the existing adaptation deficit. These studies are usually based on technical or engineering costs, e.g. in relation to the cost per m3 of delivered irrigation water or additional cm of added dike height. These studies generally show that adaptation is extremely beneficial and has low costs.

The second set of literature approaches adaptation from a different perspective. In terms of medium to longer-term adaptation (which is more directly comparable to the impact-assessment studies above), there is a focus on decision making under uncertainty. A number of studies are now using new decision-support methods, such as real options analysis, robust decision making and portfolio analysis. Implicitly, these studies usually involve higher adaptation costs when compared to I-A studies that predict-and-optimise alone (and do not consider uncertainty), as they involve some additional actions or else prioritise robustness over optimisation. However, these studies show that considering uncertainty is preferable (e.g. it can produce higher net present values) when compared to a situation where it is ignored.

A further set of literature within the iterative framing is on the costs and benefits of early low-regret options. This targets current climate variability and early resilience, thus the timing differs to most I-A studies.

A review of this literature – as part of this study - has found that many low-regret options exist which have high benefit to cost ratios. Many of these options have potentially lower costs or offer wider co-benefits when compared to engineering based options (as identified by Agrawala et al. (2011), though estimates for capacity building and non-technical options are rare, as these are more challenging to appraise in economic terms.

However, an analysis of more practical- and policy orientated studies reveals a number of issues with these estimates, which also has relevance for the technical costs from the I-A studies and for decision making under uncertainty.

First, a lesson from policy-orientated studies is that adaptation costs are often higher when working with the current policy environment, multiple risks and wider non-climatic drivers. This may be because of existing standards of acceptable risks are high (see earlier discussion of coastal risks) or because of the need to balance many competing factors in appraisal, in addition to climate change.

Second, there are important opportunity and transaction costs associated with implementation that lead to much higher out-turns in practice (i.e. ex post). This finding should not come as any surprise. It replicates a lesson from the mitigation domain, where it was found that negative cost options (no-regret) were rarely as easy or as cheap to implement as predicted in the technical cost-curve analysis (Ecofys, 2009). This was due to a range of barriers, from lack of information, company or household inertia, difficulties implementing policy measures, or capital intensity, that meant there were a large number of 'hidden costs'. Some illustration of how large this effect can be can be found in the mitigation literature: for example, Enviros (2006) reported that the inclusion of such costs reduced cost-effective opportunities by between 10-30% in the buildings sector.

This literature review for adaptation has started to identify similar issues. Many of the low or no-regret options in the adaptation domain have important opportunity, transaction or policy costs (DFID, 2014), which are not included in most current estimates. As an example, climate smart agriculture options tend to have high opportunity costs from labour and land or up-front cash outlays (McCarthy et al., 2011) while coastal ecosystem based adaptation or set-back zones can have high land acquisition / land opportunity costs that significantly reduce the attractiveness of these options compared to other options (Cartwright et al., 2013). Many ecosystem based options require enforcement to ensure effectiveness (Watkiss et al., 2014).

Even options that are widely considered as no-regret and have low implementation costs, such as heat alert systems, often exclude resource costs (Hunt et al. 2010), which will rise with climate change due to more frequent threshold exceedance

This combination of reasons is likely to mean that the costs of adaptation are likely to be higher than estimated in the current global or national estimates, noting the exact difference will vary with sector, option and context. Further work to identify and include these various costs is a priority.

In the LDC context, there are also additional challenges. There is an issue of the transferability of (ex ante) estimates for costs and benefits to the developing country context, as implementation in these countries will be more challenging due to the existing capacity, development and governance challenges, and there may be additional technical assistance and programming costs. Furthermore, there is the issue of the existing adaptation deficit, which matters because it affects the effectiveness of future adaptation.

As the evidence grows, and diverges, it is becoming more difficult to directly compare studies and sectors, and especially to aggregate estimates, because of the diversity of methods, assumptions, treatment of socio-economic change, discount rates, etc. This cautions against the simple reporting of the costs of adaptation. It also limits the potential for simple look-up tables or databases of costs and benefits. Indeed, there is an increasing recognition that the transferability of estimates is a key issue, and considerable care should be taken in reporting and compiling estimates.

Finally, it is highlighted that the evidence base in this area is still emerging. There is an urgent need for more empirical studies, to address key gaps, as well as ensuring existing information and lessons are shared. Further work in this area is being progressed by the ECONADAPT project, and the existing estimates – as well as guidance on use and transferability - will be published as the project is finalised.

Updated coverage of the sectors in the adaptation literature

Risk / Sector	Coverage/ Discussion	Cost estimates	Benefit estimates
Coastal zones and coastal storms	Comprehensive coverage (flooding and erosion) at global, national and local level in I-A studies. Good evidence base on early low regret options and long-term iterative adaptive management including policy studies and decision making under uncertainty.	✓✓✓	✓✓✓
Floods including infrastructure	Growing number of I-A adaptation cost and benefit estimates in number of countries and local areas, particularly on river flooding. Evidence base emerging on low regret options and non-technical options. Some applications of decision making under uncertainty.	✓✓	✓✓
Water sector management including cross-sectoral water demand	Recent supply-demand studies at national level, and a range of global, river basin or local studies available. Focus on supply, engineer measures; less attention on demand, soft, and ecosystem-based measures (and non-market values). Some examples of decision making under uncertainty, particularly RDM.	✓✓	✓
Other infrastructure risks	Several studies on road and rail infrastructure. Number of examples of adaptation costs for wind storm and permafrost.	✓	✓
Agriculture (multi-functionality)	High coverage of benefits of farm level adaptation (crop models), and some costs and benefits from I-A studies at global and national level. Evidence base emerging on low regret adaptation, e.g. climate smart agriculture (soil and water management).	✓✓	✓✓
Over-heating (built environment, energy and health)	Good cost information on heat-alert schemes and some cost-benefit studies for future climate change. Increasing coverage of autonomous costs* associated with cooling (I-A studies) at global and national level. Growing evidence base on alternative options for built environment (e.g. passive cooling).	✓✓	✓
Other health risks	Increasing number of studies of preventative costs for future disease burden (e.g. water, food and vector borne disease), but coverage remains partial.	✓	✓
Biodiversity / ecosystem services	Low evidence based, with limited number of studies on restoration costs and costs for management of protected areas for terrestrial ecosystems.	✓	
Business, services and industry	Very low – very few quantitative studies found, except for tourism, where some studies of winter tourism and some studies of autonomous adaptation from changing summer tourism flow*.	✓	✓

Key:

✓✓✓ Comprehensive coverage at different geographical scales and analysis of uncertainty

✓✓ Medium coverage, with a selection of national or sectoral case studies.

✓ Low coverage with a small number of selected case studies or sectoral studies.

The absence of a check indicates extremely limited or no coverage.
I-A = impact assessment
*note can be considered an impact or an adaptation.

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