ECONADAPT
The Economics of Adaptation
Funded by
the European Union

Using cost and benefits to assess adaptation options

Authors: Aline Chiabai, Alistair Hunt, Ibon Galarraga, Manuel Lago, Josselin Rouillard, Elisa Sainz de Murieta, Alina Tepes, Jenny Troeltzsch and Paul Watkiss

Deliverable number	3.1A
Work Package Number	3
Submission date	xxx
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Using cost and benefits to assess adaptation options
Authors:	Aline Chiabai, Alistair Hunt, Ibon Galarraga, Manuel Lago, Josselin Rouillard, Elisa Sainz de Murieta, Alina Tepes, Jenny Troeltzsch and Paul Watkiss
Other Contributors	Jeroen Aerts, Anne Biewald, Francesco Bosello, Areti Kontogianni, Ekko van Ierland, Petr Havlik, Onno Kuik, Reinhard Mechler, Paolo Scussolini and Michalis Skourtos
Date:	2015/11/19
Contact details	Ibon Galarraga (ibon.galarraga@bc3research.org)
Work Package Number	WP3
Deliverable number	D3.1A
Filename:	Deliverable 3_1A_20151119
Document history:	Draft/ Final and version number
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	
Copyright:	

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

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

For further information on the ECONADAPT project, please contact Alistair Hunt at: ecsasph@bath.ac.uk

Table of Contents

1 Introduction

This report is the result of the work carried out under Methodological “Work Package 3”, and more specifically Task 3a – Sub-task 1. The primary objective of this task was “to provide protocols on methodological linkages from micro level data to the macro level” and “developing guidelines for transferring data between sites with micro level data and sites without such a data; and between macro level data and micro level requirements”.

The first step in order to achieve the objectives defined for this first task of WP3 was to review the latest evidence on the costs and benefits of adaptation, and draw out some of the key findings and emerging insights that could later be used to transfer values to other scales or geographic locations.

The report explores the use of information on the costs and benefits of adaptation to justify the case for action and prioritise resources to deliver the greatest benefits. Results of national and global studies are provided. The latest detailed estimates are provided for the following sectors: energy, health, agriculture, infrastructures, coastal zones, water management and biodiversity and ecosystem services.

Transferability of data is a hotly debated issue in the economic literature. A number of challenges and difficulties were found in relation to data transfer which has hampered the application of a formal statistical meta-analysis. The study thus focused on evaluating options for transferring economic data on costs and benefits for adaptation decision-making, taking sea-level rise as an example.

The structure of this deliverable is as follows: Section 2 provides an introduction of the costs and benefits of adaptation. Section 3 describes the methodological challenges found to go from theory to practice. Section 4 presents the current state of the literature, including global and national estimates, while Section 5 focuses on in-depth sectoral estimates. Section 6 discusses the issue of transferability of economic data on costs and benefits for adaptation decision-making. Section 7 discusses the main findings of this report.

2 The costs and benefits of adaptation

The analysis of the costs and benefits of adaptation plays an important role in justifying the case for action, and for prioritising available resources to deliver greater social, environmental and economic benefits. This information is relevant at the global level, as an input to the discussion on international financing needs. It is also relevant for national adaptation plans to allow efficient, effective and equitable strategies, and for local and project level adaptation, as a key input to appraisal.

In theory, a common framework can be used for the analysis of costs and benefits at all three geographic levels (Boyd et al., 2004; Stern et al., 2006), and this has been widely adopted. This framework first assesses the impacts and economic costs of climate change, including 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. 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. The most effective (or even economically optimal) level of adaptation will therefore be a balance between the costs of adaptation measures, the benefits of adaptation measures and residual impacts.

More recently, the discussion around climate change has shifted towards a focus on risk (IPCC, 2014a), which is reflected in this report. This leads to some changes in the terminology compared to the framework above, with future climate risks (rather than impacts) and residual risks remaining after adaptation. In a risk framework, the costs of adaptation referred to below are equivalent to investments in risk reduction. More fundamentally, it has led to a change in the framing around adaptation, moving away from the previous impact-assessment framework towards iterative climate risk management.

Against this background, this chapter outlines some of the main issues with assessing the costs and benefits of adaptation, including an overview of the current state of the evidence base, set in the context of this new risk framework. It draws on the research, analysis and review of the ECONADAPT project, funded by the European Union's Seventh Framework Programme for research, technological development and demonstration[1] and co-funding provided by the UK Department for International Development and Canada's International Development Research Centre[2]. The chapter briefly introduces the challenges involved in estimating the costs and benefits of adaptation. It then assesses different evidence lines at global, national and sectoral levels. Significantly, this moves beyond the previous framing of adaptation, to consider early, practical adaptation under uncertainty. Finally, the findings from the review are highlighted and gaps identified. A more detailed review – including more detailed estimates for developing counties and more information and analysis of the studies and cost estimates – is provided in a supporting ECONADAPT report (2015) on the *Costs and Benefits of Adaptation*.

3 From theory to practice

A number of methods have been developed to derive estimates of the costs and benefits of adaptation (Watkiss and Hunt, 2010), though these have primarily used the impact-assessment framework described above. While the approach is straightforward, there are number of challenges when putting it into practice (Füssel and Klein, 2006; UNFCCC, 2009; UNEP, 2014; ECONADAPT, 2015).

- Estimating future climate risks and adaptation benefits: It is difficult to estimate the future impacts and economic costs of climate change, due to the wide range of potential risks, the scientific and economic information available, data gaps and modelling constraints. These issues are amplified when considering adaptation costs and benefits, especially given the large number of potential adaptation options that exist.

- Uncertainty: The challenges above are made more difficult because of the large uncertainty associated with future climate change. At the current time it is not clear what future emission pathway the world is on, and even if this were known, significant climate model uncertainty would remain. Taking account of this uncertainty has two consequences: it makes it harder to estimate the scale of the impacts of climate change and the benefits of adaptation; and it increases adaptation costs relative to a situation where people are assumed to be able to predict the future.

- Framing: The costs and benefits of adaptation are determined by the framework that is used and the objectives that are set (e.g. whether the optimal level is based on economic efficiency versus a defined level of acceptable risk). These vary with context, country and across stakeholder groups. This means it is very difficult to provide a definitive cost of adaptation. There are also additional issues around the distributional effects (and equity) of climate change over time and between groups, and whether these are accounted for when analysing impacts and adaptation.

- Baselines and timescale: The baseline assumptions, and the future timescales under investigation, lead to large variations in estimates. The choice of discount rate is of particular relevance in this context, as it affects the weight put on benefits occurring in the future. There is the further issue of the existing adaptation deficit (the gap between the current state of a system and a state that minimises adverse impacts from existing climate variability), as adaptation to future climate change will be less effective if this deficit has not first been addressed (Burton, 2004). This is a particular problem for developing countries, but even OECD countries have adaptation deficits or are close to the limits of coping with current climate variability (ASC, 2011).

- Scale and boundaries: The impacts of climate change in one area will spill over into other areas through mechanisms such as trade and financial flows. These can only be modelled at a global scale, but can affect costs reported at the regional, national or local scale.

The assumptions used to address these challenges can have a large impact on results. A consequence of this is that the results of any study – and the estimates of the costs and benefits of adaptation they produce – have the potential to be misleading if viewed in isolation. It is important for any study to be transparent about the assumptions used and implications of these on potential decisions.

Finally, one of the key aims of investigating the costs and benefits of adaptation is to help allocate resources, to inform national adaptation planning by governments through to local decisions. The impact assessment (I-A) framework outlined above reflects a stylised model of reality: It calculates technical costs, which are used to estimate the reduction in future damages. While such studies are useful for raising awareness, and generating headline estimates of the costs and benefits, they are less useful for practical (early) adaptation as they are highly theoretical. More recent studies highlight an emerging set of challenges in addition to those listed above (ECONADAPT, 2015):

- 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). Building adaptive capacity involves sharing information, research, monitoring, raising awareness, education and training, and other institutional and organisational activities (UKCIP, 2006). It is a key priority for government in creating the enabling environment for adaptation. However, it is often omitted in technical studies, and its indirect nature makes it difficult to assess costs and benefits. There has been some progress in considering the value of information in relation to climate services and adaptation (Clements, 2013; Macauley, 2010) but this remains a priority.

- Wider issues and policy context: As adaptation moves towards implementation, there is a greater need to include wider (non-climatic) drivers and existing policy in analysis. Earlier studies, particularly those that use an I-A framework, ignore these factors (Füssel and Klein, 2006; UNFCCC, 2009), yet these are often more influential than climate change, particularly in the short-term.

- Autonomous and private sector adaptation: Autonomous adaptation will arise for many of the risks of climate change, but this has rarely been quantified, as there is a lack of empirical evidence, and it is difficult to include this in most impact and modelling assessments (with exceptions for agriculture and energy demand). While this is likely to be more reactive than planned, it remains a priority, especially for considering the potential actions of the private sector and how this can affect the nature and extent of government intervention.

- Opportunity and transaction costs associated with policy implementation: Impact assessment estimates are usually based on technical costs, but there can be important opportunity costs associated with measures, as well as the transaction costs to introduce and implement the required measures. These can have a major influence on the choice of options and the aggregate estimates of adaptation costs and benefits.

- Cross-sectoral, cross-cutting and macroeconomic interactions: 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 significantly affect the ranking of adaptation measures (Skourtos, Kontogianni and Tourkolias, 2013). At the macroeconomic level, the effects of climate impacts in one sector will feed through across the economy, though this is often omitted in studies. An emerging priority is to understand these wider economic costs of adaptation and their importance for public finances, GDP, employment, investment and so on.

- Decision-relevant timescales: The impacts from climate change will become most apparent from the middle of the century onwards, and this is when many studies focus their efforts. However, there is less policy relevance in estimating the future costs of adaptation in 2040 and beyond. Instead, the key issue is what to do in the next decade or two, both to address early changes and to prepare for the longer-term.

- Transformative adaptation and the limits of adaptation: Incremental adaptation helps to maintain the essence and integrity of a system or process at a given scale, while transformational adaptation changes the fundamental attributes of the system (IPCC, 2014). There is, as yet, little economic evidence on transformational adaptation. This is increasingly important given the recognition of the limits of adaptation (Adger et al., 2007), including physical and ecological limits, technological limits, financial barriers, information and cognitive barriers, and social and cultural barriers. These limits are omitted in most current studies and are a critical gap.

In response to the various challenges of adaptation costing, and these emerging issues, the framing of adaptation has changed in recent years, moving away from a focus on science-first and impact assessment. In particular, the use of iterative climate risk management to consider uncertainty has emerged (see Chapters 4 and 6), which considers climate and non-climate risks as a dynamic set of risks, and identifies phased adaptation responses. These changes have important implications for the costs and benefits of adaptation. It is now difficult to compile and compare estimates, because of the different approaches being used. Studies use different methods, objectives, metrics and assumptions, and often focus on different time periods, and are conducted at different scale and geographical resolution. No method is absolutely right or wrong and they all have strengths and weaknesses according to the objectives of the exercise and the specific application. However, there is a major difference between earlier and later studies, and they are reported separately in the review below. The focus is therefore on assessing the state-of-the-art and key lessons, rather than providing absolute estimates of the costs of adaptation.

4 Current state of the literature

Over the past few years, there have been several reviews of the costs and benefits of adaptation (EEA, 2007; OECD, 2008; UNFCCC, 2009; Agrawala et al., 2011a; Markandya et al., 2014; Chambwera et al., 2014). These report that the evidence base is relatively small and stress that deriving estimates involves many challenges, and that different studies have used different methods, time scales, climate scenarios, objectives and assumptions, making comparisons difficult. As estimates of the costs (and benefits) of adaptation are conditional on the assumptions and data sources used, there are large variations in estimates for countries and sectors between studies. Estimates will also be highly context specific and will vary with existing national, sectoral and individual preferences, as well as analysis and choice of metrics.

There are, however, a growing number of national level initiatives, varying from one or two key sectors through to economy wide assessments. There are also more sectoral studies that focus on early adaptation. These two factors have led to a much larger number of studies – and evidence – on the costs and benefits of adaptation. A recent major review and compilation of these studies (ECONADAPT, 2015) has identified around 500 studies and an early review of these form the basis of this chapter. While the review has aimed to be comprehensive as possible, there will inevitably be additional relevant studies, especially given the rapid emergence of this literature.

The review as evidence is summarised in Table 1 next, taken from the supporting ECONADAPT report. While coastal risks remain the most comprehensively covered, more literature has emerged for other risks and sectors. There is also a greater geographical coverage, as shown in Figure 1. However, while the evidence base is growing, and the coverage has expanded, it remains partial for all sectors (regarding, for example, impacts, spatial and temporal scales, benefit estimates) and major gaps exist for ecosystems, business and industry. These studies also use a diverse set of methods, socio-economic assumptions, cost metrics and benefit categories, as well as discount rates. This makes inter-comparison difficult. Finally, the number of more policy orientated and iterative studies remains low. The review therefore cautions against the simple reporting of the costs of adaptation and further analysis of transferability is a key research priority. The following sections compile the evidence and lessons, starting with the global assessments, and then providing national and risk- and sector-based estimates.

Table 1. Updated quality of the 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 impact assessment studies. Good evidence base on early low regret options and iterative adaptive management including policy studies and decision-making under uncertainty (real options).	✓✓✓	✓✓✓
Floods including infrastructure	Growing number of adaptation cost and benefit estimates (impact assessment studies) in a 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	A recent focus on supply-demand studies at the national level, but a range of global, river basin or local studies are available. Focus on supply, engineering measures; less attention to demand, soft, and ecosystem-based measures. Some examples of decision making under uncertainty, particularly robust decision making, with policy relevant studies.	✓✓	✓
	Several studies on road and rail infrastructure. Examples of wind storm and permafrost.	✓	✓
Agriculture (multi-functionality)	High coverage of the benefits of farm level adaptation (crop models), and some benefits and costs from impact assessment studies at global and national level. Evidence base emerging on potential low regret adaptation, including climate smart agriculture options (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 costs1 associated with cooling from impact assessment studies (global and national). Growing evidence base on low-regret options for built environment (e.g. passive cooling).	✓✓	✓
Other health risks	Increasing 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 base, with a limited number of studies on restoration costs and costs for management of protected areas for terrestrial ecosystems.	✓	
Business, services and industry	Very few quantitative studies available, except for tourism, some focusing on winter tourism and some on autonomous adaptation from changing summer tourism flows.[1]	✓	

Note: See main text for discussion and caveats.

1.can be considered an impact or as autonomous adaptation. (i.e. unplanned).

Key:

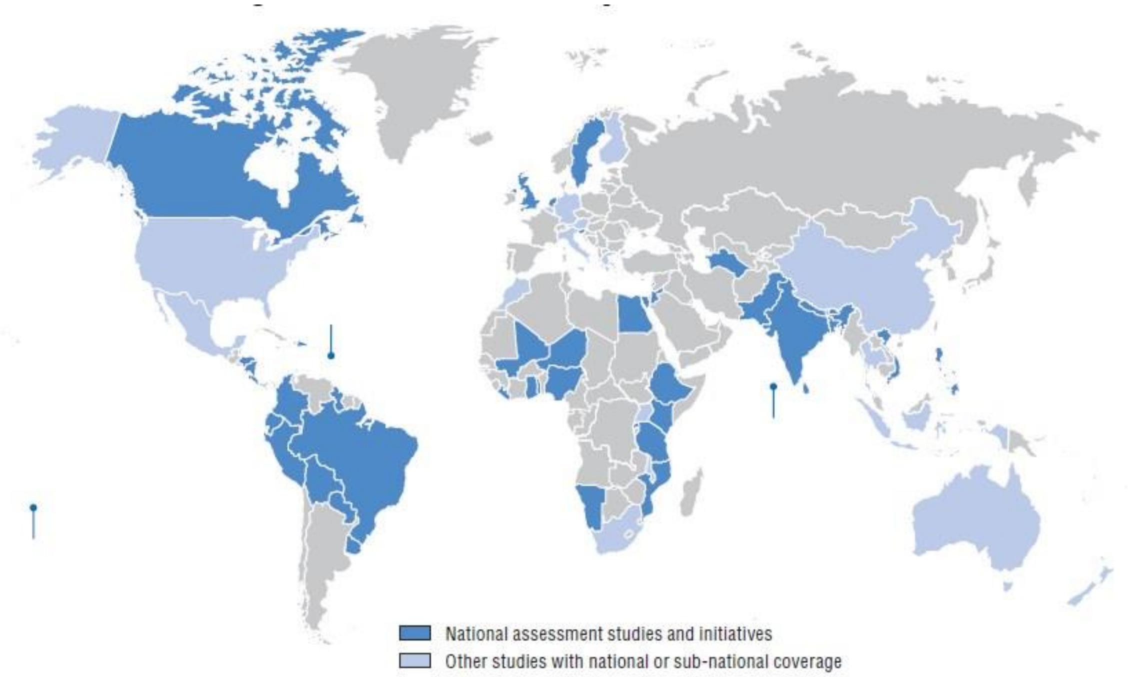
✓✓✓ Comprehensive coverage at different geographical scales and analysis of uncertainty.

✓✓ 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.

Source: ECONADAPT (2015), “The Costs and Benefits of Adaptation”, results from the ECONADAPT Project, ECONADAPT consortium.

Figure 1. National level adaptation cost studies



Source: ECONADAPT (2015), "The Costs and Benefits of Adaptation", results from the ECONADAPT Project, ECONADAPT consortium.

4.1 Global estimates

Early estimates of the global costs of adaptation focused on the period to 2030. Six assessments were undertaken (OECD, 2008), which primarily estimated costs using an investment and financial flow analysis method. This applies an adaptation cost "mark-up'' to future investment plans to take account of future climate change. 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 was the study by the United Nations Framework Convention on Climate Change, which estimated global adaptation investment needs at USD 50 to USD 170 billion per year by 2030 (equivalent to 0.06-0.2% of projected GDP), primarily associated with infrastructure protection in developed countries (UNFCCC, 2007). This study estimated that only USD 30 to USD 70 billion per year would be required for adaptation investments in developing countries. However, a critique by Parry et al. (2009) argued that this study underestimated adaptation costs by a factor of 2 to 3, and stressed that many sectors and impacts were not included.

A subsequent assessment – focusing on developing countries – was undertaken by the World Bank in the Economics of Adaptation to Climate Change (EACC) study (2010). This study used impact assessment to estimate the economic costs of climate change, then estimated the costs of adaptation to achieve pre-climate levels of welfare. The total adaptation cost for developing countries was estimated at USD 70 billion to USD 100 billion per year (using 2005 nominal values). This estimate reflects the average projected costs between 2010 and 2050 for a 2 °C warmer world.

The World Bank estimate is slightly higher than the UNFCCC study for similar regions. This study found that the projected costs were highest in East Asia and the Pacific Region, and for infrastructure, coastal zones and the water sector. The study reported costs rising from USD 60 to USD 70 billion per year by

2010-19 to USD 90 to USD 100 billion per year by 2040-49. The study considered two climate futures: i) minimum and maximum temperature, and ii) “wetter” and “drier” projections. It found higher costs with wetter scenarios due to infrastructure impacts. The choice of aggregation rule also affected the size of the estimates, notably whether gains from climate change were added to adaptation costs. However, as the report acknowledges, adaptation costs were still calculated as though decision makers know the future with certainty. Moreover, many of the criticisms of Parry et al. (2009) still apply, including that the coverage of impacts and sectors is partial.

Finally, an alternative set of global estimates has been derived from global economic integrated assessment models (IAMs). These quantify the economic impacts of climate change, and in some cases, the costs and benefits of adaptation, see Box 3.1. They tend to focus on the long-term, and have been used to assess mitigation and adaptation costs. Most adaptation estimates are based on the AD-RICE or PAGE models (see Parry et al., 2009; de Bruin et al., 2009; Agrawala et al., 2011a; Bosello et al., 2013; Dellink et al., 2014). More recent assessments, notably de Bruin (2014), assess how adaptation costs could vary along different emission pathways, finding costs could be around twice as high in a 4 °C scenario than a 2 °C one, even by 2050. These IAMs have also been applied at the continental level, including by the Asian Development Bank (ADB, 2014) for the Economics of Climate Change for South Asia.

Box 3.1. Consequences of climate change damages for economic growth: OECD assessment

The OECD’s dynamic global general equilibrium model, ENV-Linkages, assesses the consequences of a selected number of climate change impacts in the various world regions at the macroeconomic and sectoral level. The analysis estimates that the climate change impacts on annual global GDP are projected to increase over time, leading to a global GDP loss of 1.0% to 3.2% by 2060 for the most likely equilibrium climate sensitivity range, with the greatest impacts on the agricultural sector. Nevertheless, some impacts and risks from climate change have not been quantified in this study, such as large-scale disruptions. They will potentially have large economic consequences, and on balance the costs of inaction estimated in this study are likely to underestimate the full costs of climate change impacts.

Source: Dellink, R. et al. (2014), “Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment”, *OECD Economics Department Working Papers*, No. 1135, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz2bxb8kmf3-en*. OECD (2015), “The economic consequences of climate change”, forthcoming September 2015.

4.2 National estimates

A large number of national studies that consider the costs and benefits of adaptation have emerged in recent years. An indicative mapping of these studies is shown in the Figure 1, compiled by the ECONADAPT project (2015) and summarised below.

4.2.1 OECD countries

A number of national level assessments have considered adaptation costs and benefits in OECD countries. In the survey undertaken for this report, Netherlands, the United Kingdom, and Slovenia reported that economic assessments were included in their national adaptation programmes. The first two of these reflect some of most advanced examples globally. They have evolved over many years, from early impact assessment, to analysis of adaptation options and possible costs (UKCIP, 2006; van Ierland et al., 2006), and finally to advanced iterative frameworks with the Delta programme in the Netherlands (Delta Programme, 2011; Delta Programme, 2014; Eijgenraam et al., 2014) and the United Kingdom's Economics of Climate Resilience and the National Adaptation Programme (Watkiss and Hunt, 2011; Frontier Economics, 2013; HMG, 2013).

There are also studies in other European countries that have costed adaptation. 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 options (Carraro and Sgobbi, 2008) and a study in Germany undertook cost-benefit analysis on 28 potential adaptation options (Tröltzsch et al., 2012). At the European level, there are academic studies that have considered several sectors, such as the PESETA (Ciscar et al., 2011) 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 (Dore and Burton, 2001). This was followed by numerous studies in specific sectors and regions (see Environment Canada, 2006; NRC, 2007; NRTEE, 2011). Similarly, in the United States, there are national level studies that provide estimates in specific sectors or regions. While the recent US National Assessment (2014) did not compile national adaptation costs, a recent review (Sussman et al., 2014) summarised the current state of knowledge. There are also many state-level climate change-specific adaptation actions that focus on planning and include an analysis of adaptation costs.

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 per year (Delta Commissie, 2008) and similar annual costs have been estimated for the United Kingdom (Foresight, 2004; EA, 2008; EA, 2011; ASC, 2014). In the United States, 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. For example, recent adaptation cost studies or initiatives have commenced in Austria, Spain and Mexico.

4.2.2 Developing countries and emerging economies

In recent years, a number of initiatives have emerged that estimate the costs of adaptation in developing countries and emerging economies. While the focus of this chapter is on OECD countries, these studies provide a large additional source of evidence. They also provide important practical lessons from the early implementation of adaptation, which is advancing rapidly in many of these countries. The estimates are also highly relevant to OECD countries because they can help to inform international development assistance for adaptation. The evidence base includes:

- The World Bank's EACC country studies (in Bangladesh, Bolivia, Ethiopia, Ghana, Mozambique, Samoa, and Viet Nam), which used impact-assessment, but also provided more detailed (bottom up) assessment and considered economy wide effects (World Bank, 2010).

- The United Nations Development Programme (UNDP) Investment and Financial Flows initiative (UNDP, 2011) estimated the costs of adaptation through to 2030 in 15 countries (Bangladesh, Colombia, Costa Rica, Dominican Republic, Ecuador, Gambia, Honduras, Liberia, Namibia, Niger, Paraguay, Peru, Togo, Turkmenistan, and Uruguay) for 1 or 2 key sectors.
- The UNFCCC National Economic, Environment and Development Study (NEEDS) assessed the short- and long-term costs of adaptation and financing needs in Egypt, Ghana, Jordan, Lebanon, Maldives, Mali, Philippines and Nigeria (UNFCCC, 2010).
- Additionally, a large a number of other regional and country level studies have been undertaken, including in Bangladesh, Brazil, Bhutan, China, Ethiopia, Guyana, Kenya, India, Indonesia, Maldives, Nepal, Philippines, Peru, Rwanda, Samoa, South Africa, Sri Lanka, Tanzania, Thailand, Uganda and Viet Nam, as well as Caribbean and Central America regions. Details are provided in ECONADAPT (2015).

The evidence from these studies provides some new insights. They suggest that adaptation costs for these countries are potentially higher than reported in the EACC study in the period up to 2030 and beyond (UNEP, 2014). This can, in part at least, be explained by the coverage of the risks, the consideration of higher levels of temperature change (beyond 2 °C), the challenge of uncertainty, and the consideration of the existing adaptation deficit. It also reflects the emerging experience that implementation of measures entails costs beyond the technical cost of the measure itself.

5 Sectoral estimates

Many studies report estimates on a sector by sector basis, e. g. OECD (2008) review. This provides a useful entry point, but in many cases adaptation is a response to a cross-sectoral risk (e.g. floods or heat waves), thus there is the potential for co-ordinated responses to share costs, generate co-benefits and address potential conflicts. For this reason, it is useful to consider cross-sectoral risks as well as individual sectors, and this is the format used below. As highlighted above, this section summarises the state of evidence and potential lessons and insights. More detailed cost estimates are presented in ECONADAPT (2015).

5.1 Energy sector

5.1.1 Revision process

The work undertook for this sector has included the systematic review of over 60 papers, which made it possible to obtain all relevant literature - unpublished grey literature and research findings, as well as published peer-reviewed journal articles - on the impacts and adaptation of the energy sector to climate change. Table 2 summarises the main findings of the literature review, which are further explained in the next section.

Table 2. Summary of the main impacts and adaptation options in the energy sector.

Principal impacts in the EU	Principal consequences of impacts in the EU	
	Consequences	Description
Changes in primary energy availability	Hydropower potential loss	A loss of annual energy that is potentially available for all existing hydropower stations due to climate change. (Echaeffer et al. 2012)
	Wind power potential	Alteration of distribution and variability of wind due to climate change could affect positively or negatively on wind power potential
	Solar power potential	A modification in solar radiation due to different factors will directly affect numerous regions causing gainers and losers (Bartok 2010)
	Wave energy potential	Is created through the transfer of energy from wind over water bodies and it will face changes (Vikebo et al., 2003)
	Availability of biofuels	Changes in temperature and levels of carbon dioxide may affect agricultural production in general and therefore availability of biofuels (Hatfield, 2010)
	Availability of fossil fuels	Its availability may be affected by impacts on the access to reserves of fossil fuels (2011)
Changes in the capacity to supply energy to consumers	Impacts on energy-transforming technologies	Impacts in the facilities operating that transform energy (Vicuña 2007)
	Impact on transmission, distribution and transfers	These are the impacts that are produced through the affection or disruption of different infrastructures
Changes in energy consumption patterns	Reduction of heating demand and increasing of cooling systems	Due to a climate change (to a warmer climate) there will be a higher cooling need and a lower heating system need
Vulnerability of energy infrastructures	Sitting infrastructure	Increased extreme events such as flooding from sea level rise, coastal erosion, could affect for instance the necessary water availability for the operation of energy infrastructures
	Downtime and system bottlenecks	Extreme weather could affect the operation of energy systems due to impacts on isolated infrastructures
	Energy trade	Extreme weather could create (cold spells and heat waves) an increased stress on the transmission, distribution and transfer of energy.

Adaptation measures based on different attributes		
Building Adaptation Capacity measures		
Measure		Description
Access to information		1. Assuring consistency of data (Troccoli et al., 2010) 2. Providing ready and reliable access to data and forecasts of some weather services 3. Giving importance to research as it is vital in projecting future scenarios and giving responses to them (Unep, 2006)
Supportive social structures		1. Clear and good policies are those which have been created by consulting the experts 2. Involvement of local institutions vital for planning and implementing proper policies and projects (Agrawal et al., 2008) 3. Promulgating multi-sectorial partnerships between different actors is important
Supportive governance		1. Providing clear policy framework to social and economic agents by governments 2. Creating an integrated planning within energy and other sector as some of them are closely linked. example; water sector 3. Providing by international governance capacity for adaptation (international funding streams. "The Global Environmental Facility")
Delivering adaptation actions measures		
Measure		Description
Preventing effects or reducing risks	Hard adaptation measures	Invest in infrastructure to protect energy infrastructures from climate change events
	Soft adaptation measures	1. Reconsidering the location of investments (Neumann and Price 2009) 2. Anticipating the arrival of a climate hazard through the development of meteorological forecasting 3. Changes in the operation and maintenance of existing infrastructures 4. Technological changes and improved design of infrastructures
Sharing responsibilities for losses and risks		Insurance should be provided to most affected and effectible sectors. Example; weather risk management facility (WRMF)
Exploiting opportunities		1. Building a more decentralized energy structure, preferably based on renewable energy sources situated in safe places 2. designing better urban and land planning to reduce energy consumption

5.1.2 Main findings

Changes in primary energy availability

Climate change can affect primary energy availability. Decreased precipitation has an impact on hydropower production. Increases in the number of cloudy days and changes in the precipitation type will affect solar power generation. Climate change can either increase or reduce wind speeds. Higher temperatures result in decreased efficiency in combustion turbines and nuclear power output.

Hydropower potential

A loss of annual energy that is potentially available from all existing hydropower stations due to climate change. In general, climate change is expected to decrease precipitation and change river flows thus having a direct impact on hydropower production. This impact has been analysed for Europe, United States, Africa and Latin American Countries. Lehnera, et al. (2003) reported that future alterations in discharge regimes will lead to unstable regional trends in hydropower potentials, with reductions of 25% and more for southern and south-eastern European countries. In Macedonia, the annualized cost of replacing lost hydropower production due to climate change with coal, gas and nuclear alternatives is estimated at 10^6 EUR/year, same as with renewable energy alternatives (Callaway et al., 2011a). Energy efficiency measures can help to reduce consumption and reduce pressure to produce more energy (Callaway et al., 2011b). Within a changing climate scenario, the planned investments in the hydropower sector should be "climate resilient".

Hydropower production is estimated to fall by the end of the century, losses ranging from 5%, in the low emission scenario B1, to 12% in the high emission scenario A2 (Sainz de Murieta, et al., 2015). Brazil's hydroelectric generation system was found to fall by 31% and 29% in the A2 and B2 scenarios, respectively (de Lucena et al., 2010). Although no aggregate relevant impact on average electricity generation was reported, the loss in average electricity generation is above 80% in some places.

According to the World Bank Group (2010), total hydropower production will decrease in Ethiopia under different scenarios. Additional dams and power stations, as well as new dam sites on parallel rivers, can be used to develop greater energy generation potential for the same river flow. The annual undiscounted cost of bringing on additional plants over the 2010 to 2050 period is estimated at $100 million. Hydropower losses in Kenya related to climate change will be 4 million $ in a low climate change scenario, and 19 million $ in a high climate change scenario (Droogers, P., 2009).

The effects of climate change on Federal Hydropower in the United States have been analysed by the US Department of Energy (2013). In the near-term period (2010-2024), the mean change in annual generation for Bonneville region was projected to be an increase of 1.3 billion kWh (less than 2% relative to the historic mean generation from 1989-2008). In the mid-term period (2025-2039), the mean change in annual generation was projected to be an increase of 2.6 billion kWh. In the Western region, annual precipitation was projected to be generally comparable to baseline conditions and mean annual hydropower generation was projected to increase for both near-term and mid-term periods. In the South-western region, hydropower generation indicated a 0.1 billion kWh (1.8%) reduction in the near term and 0.5 billion kWh (7.7%) reduction in the mid-term period, relative to the historic observation from 1989-2008. In the South-eastern region, the mean projected change in annual federal hydropower generation is a 0.27 billion kWh (3.6%) increase in the near-term period and nearly no change in the mid-term period. Washington and Oregon will together lose $1.7 billion in annual revenues from hydropower by 2080 because of declining snowpack and water shortages (Union of concerned scientists). Even if the most severe climate change does not occur, analysts project that California could lose 10–20 percent of its hydropower at a cost of $440 million–$880 million annually (Franco, G., and A.H. Sanstad, 2006). Similar results were reported by Vine, E., (2008) that stated that a 10 percent decrease from the current average in-state level of hydropower generation would result in an additional $350 million per year in net replacement costs. In the Colorado Basin, a 1 percent drop in precipitation suggested by some authors will decrease hydropower generation by 3 percent (GAO, 2014). In California, average annual hydropower production could potentially decrease by as much as 15 percent by 2020 and 30 percent by 2050 compared to baseline hydropower production. (Vine, E., 2008).

Using macro-scale hydrological models used and a CGCM1 model projection, Bates, B.C., et al. (2008) found Ontario's Niagara and St. Lawrence hydropower generation would decline by 25–35% by 2070 (2°C global warming scenario), resulting in annual losses of Canadian 240–350 M$ at 2002 prices. With the HadCM218 climate model a small gain in hydropower potential (+3%) was found, worth approximately Canadian 25 M$ per year. Lower water levels of Great Lake in Canada could lead to large economic losses (Canadian 437–660 M$ per year).

Based on the Certified Emission Reduction, for a total mini-hydraulic output in the RE scenario is 74 MW, the total potential reduction in CO2 emissions will be 2.553 million tons. The total income from MH under the CDM will be V25.02 million (Alka Sapkota, Zhibo Lu, Haizhen Yang, Juan Wang, 2014). The public and private investment needed for adaptation in the hydro-power sector in Nepal is estimated to be around US$500 million (IDS NEPAL, PAC and GCAP, 2013).

Wind power potential

Alteration of distribution and variability of wind due to climate change could affect positively or negatively on wind power potential. Vine, E., (2008) associated increased CO2 concentrations with increased cloudiness, resulting in reduced wind speeds of 1.0 to 3.2 percent in the next 50 years and 1.4 to 4.5 percent over the next 100 years. In Brazil, the increase in the average wind velocities in the coastal regions in general and in the north/northeast regions of the country in particular, will make the exploitation of the wind power potential very attractive in the coastal regions (Andre´ Frossard Pereira de Lucena, Alexandre Salem Szklo, Roberto Schaeffer, Ricardo Marques Dutra, 2010). For an achievable potential estimated of 37.9 GW (96.9 TWh/year), the average levelized cost for using the whole Northeastern wind power potential would correspond to 79.37 US$/MWh.

Solar power potential

Increased CO2 concentrations were associated with increased cloudiness, resulting in decreased levels of daily global radiation availability in the range of 0 to 20 percent (Vine, E., 2008; Alka Sapkota, Zhibo Lu, Haizhen Yang, Juan Wang, 2014). According with Aivalioti, S. (2015) every 1°C rise in temperature will drop the efficiency of 1 photovoltaic cell by 0.4% to 0.5% in relative terms.

Fossil fuels availability

Climate variability was found to affect electricity production in Nepal via the increased incidence of forest fires, which will threaten the availability of wood for fuel (Alka Sapkota, Zhibo Lu, Haizhen Yang, Juan Wang, 2014)

Nuclear power potential

High temperatures result in the loss of power output from nuclear power plants. During a heat wave nuclear power output can be reduced by more than 2% per 1°C rise in ambient air temperature (Aivalioti, S., 2015). France had to lower its electricity generating capacity by 4,000 megawatts (MW) during the heat wave in 2003, the equivalent of four nuclear power stations, as 17 reactors were forced to shut down (Aivalioti, S., 2015). The Tennessee Valley Authority in the US had to reduce power output from its Browns Ferry Nuclear Plant in Alabama in 2007, 2010, and 2011 because the temperature of the river was too high to receive discharge water without raising ecological risks. The cost of replacing lost power was estimated at $50 million (GAO, 2014) because 25 percent of existing electric generation in the United States is located in counties projected to be at high or moderate water supply sustainability risk in 2030. Expected efficiency losses in the nuclear plants in Asia due to climate change is small, but additional cooling towers cost approximately 67–130 M$ each, and modifications to cooling water inlets at coastal locations to allow use of cooler, deeper water may cost up to 133 M$ (Asian Development Bank, 2012).

Changes in the capacity to supply energy to consumers

The increased frequency and intensity of wildfires expected with climate change may have a significant impact on the transmission and distribution of energy (Vine, E., 2008). Temperature increases will also make power generation and transmission systems function less efficiently. For every 1°C (1.8°F) temperature increase the transformers' capacity declines 1% and the resistance of copper lines increases 0.4%. Overall, network losses increase 1% for every 3°C (5.4°F) (According to Aivalioti, S., 2015).

European energy expenditures on supply-side resources will be 65 B$ higher in 2100—or 0.08 percent of gross domestic product—in one climate change scenario (Sathaye, J., et al, 2011). Other authors estimate that the annual costs could be as high as 95 B$ in 2100, although in E1 costs reduce considerably (Watkiss, P., 2011). Net energy shortfall due to climate change in the Albanian Power Sector is estimated on the order of 350 GWh per year by 2030, equivalent to power generation from a 50 MW thermal power plant. By 2050, the shortfall rises to 740 GWh per year (105 MW), or 3 percent of total demand.

The effect of higher temperatures on the result in decreased efficiency of combustion turbines has been analysed for the US Midwest regions, where approximately 95% of the electrical generating infrastructure is susceptible to decreased efficiency due to ambient temperature change (Beecher and Kalmbach 2012). The July 2002 heat wave affected the electricity supply in California - there was an all-time single day electricity record of 52,863 - and many regions were without power for periods ranging from hours to days (Aivalioti, 2015). In Florida, every additional degree Fahrenheit of warming could cost consumers 3 B$ in electricity costs per year by 2100 (Stanton, E.A., and F. Ackerman, 2007). In New Mexico (USA), inefficient energy transmission during heat waves will cost consumers 1 B€ per year by 2080 (Niemi, 2009a).

In Nepal (IDS NEPAL, PAC and GCAP, 2013), reduction of energy supply (and the impact of planed interruptions) will have economic costs equivalent to 0.1% of GDP per year on average (0.3% in very dry years). Loss of power output and increased fuel consumption at the O Mon IV Thermal Power Plant in Vietnam are estimated to cost approximately 11.0 M$ over the period 2015–2040 (Asian Development Bank, 2012). In the 2005–2035 period, the projected efficiency of natural-gas-fired thermoelectric generation would decrease by 1.8% in Brazil, in both A2 and B2 (de Lucena et al., 2010).

New policies to adapt the energy supply system to climate change will cost 40 Trillion $ each year up to 2035, mainly from OECD countries and China: (1) Power sector: 16.4 trillion $; (2) Oil sector: 13.7 trillion $; (3) Gas sector: 8.8 trillion $ (IEA, 2014). Altvater et al, (2012) estimated costs of key adaptation measures for Europe. According to the authors, the cost to adapt electricity grids in the EU (without Malta) is estimated to be in the range of 654.1 M€ per year (under A1FI scenario) to 636.6 M€ per year (under B1 scenario) until 2025. The costs (investment and operation) of an early warning system for extreme weather events for one power plant are estimated to be in the rage of 88,620 € (worst case) to 38,010 € (best case). Cooling of thermal power plants in order to improve the efficiency and reliability of thermal power plants in EU-27 will cost 637.3 M€ per year until 2025 while high efficiency ventilation will cost from 100 M€ to 41.8 B€ per annum until 2025. The efficiency and reliability of thermal power plants may also be improved through heat-related efficiency standards, cooling technology standards, siting requirements, changing the types of turbines and using heat-resistant technology, using water recirculating systems or air-cooling technology, expanding the variety of power plant sources in the electricity mix, improving electricity storage, and modernizing the grid.

Demand-side and supply-side policies can help to adapt to this impact. Demand side-policies: reducing energy load through end-use efficiency (load reduction) as well as shifting load to off-peak periods for more efficient utilization of power plant capacity; real-time prices and demand-response programs; accelerate development and deployment of efficiency practices; National standards for appliance and fixture efficiency. Supply side policies: shifting away from reliance on greenhouse gas-emitting fossil fuels and toward clean and renewable energy alternatives; loss reduction and heat capture strategies, including cogeneration; renewable energy development.

In rural Nepal, adaptation to climate change requires efforts to deliver and upgrade social conditions (poverty reduction), economic conditions (energy security), and ecological conditions. The cost of using kerosene lighting is as high as US$3-4 per kWh, while cost of electricity generated from one of RETs is only USD$0.5-1 per kWh. Household lighting has been estimated to save between US$5e16 per month in poor households in developing countries. Based on the Certified Emission Reduction, the total income under the CDM from the biogas sector in Nepal will be V351.624 million. Similarly, for a total MH output in the RE scenario is 74 MW, the total potential reduction in CO2 emissions will be 2.553 million tons. The total income from MH under the CDM will be V25.02 million. Using a cost-benefit analysis Nadal, M., Schuhmacher, M., Domingo, J.L. (2009) calculated that the total benefit (due to the decrease in cancer) of using sewage sludge as an alternative fuel was 3.44 million euros (US$ 5.09 million).

Changes in energy consumption patterns

Climate change will increase summer cooling and reduce winter heating, affecting future energy demand. These responses are largely autonomous, and can be considered as an impact or an adaptation, though they are strongly influenced by other socio-economic factors, notably income. While in the OECD the change in energy demand will be driven by temperature, in developing countries it will be dominated by rising incomes (Arent et al., 2014).

There is a growing number of studies that assess costs of air conditioning demand. Mima, Criqui and Watkiss (2011) assessed cooling and air conditioning costs for Europe (by region), and for the United States, China and India using a least cost-optimisation energy model, but also considered the additional (discounted) cost of air conditioning units. In the European Union, cooling costs were estimated at EUR 30 billion per year by 2050, undiscounted, and three times this amount by 2100, with a strong distributional pattern and higher costs in the South. The costs of air conditioning demand in India were estimated to be extremely high, at several hundred billion USD per year (undiscounted) by the end of the century. The costs of cooling demand in the United States were also assessed by Sussman et al (2014), that reported annual costs of USD 6 billion to USD 87 billion (undiscounted) in five national studies. These studies show that the autonomous costs of increased cooling could be large, even if these are offset by reductions in heating, as in many OECD countries. If this cooling is delivered with air conditioning, this could contribute to higher greenhouse gas emissions, conflicting with mitigation objectives (unless electricity is decarbonised). However, there is the potential for air conditioning to reduce health impacts as a co-benefit (see Ostro et al., 2010).

A number of studies assess costs of future energy demand for heating and cooling together. An assessment in nine different locations worldwide found that energy demand for heating (including preparation of sanitary warm water and process heat) will increase and energy demand for cooling will reduce for the period 2000 – 2100 (Isaac, M. and Van Vuuren, D. P., 2009). In Europe, a number of authors have reported net energy and costs savings, while others have found net losses. Sathaye, J., et al (2011) reported a net gain of 470 B$: expenditure is projected to decrease by 480 B$ for heating and increase by 10 B$ for cooling. Watkiss, P. (2011) projected a reduction in heating demand of 140 B$ per year in EU27 by 2100 under the A1B scenario (around -0.17% of projected EU27 GDP in 2100) and an increase of cooling demand in the residential and service sector of 130 B$ per year by 2100 under the A1B scenario (153 B$ if we add investment costs for new air conditioning to energy costs). Using a multi-sectoral general equilibrium analysis and reckoning that uncertainties largely influence the results, JC Ciscar (ed.), L Feyen, C Lavalle, A Soria, F Raes (2014) found net energy savings of 7% for Europe under the 2°C scenario. Energy consumption would fall in all EU regions with the exception of the Southern Europe region, where demand would rise by 8%. The Central Europe North region is the one with the highest fall in energy consumption (-21%). Based on the assessment of energy demand for heating and cooling in 30 EU countries, Eskeland, G., S. and Mideksa, T., K. (2009) suggest that random weather variations have a statistically significant impact on residential electricity demand for heating and cooling. With climatic changes, Northern Europeans will reduce their heating demand and Southern Europeans will increase their cooling demand. The future heating and cooling energy demand of German residential buildings has been analysed in Olonscheck, M., Holsten, A. and Kropp, J. P. (2011), that concluded that demand for heating will decrease substantially until 2060 (this shift will mainly depend on the number of renovated buildings and climate change scenarios and only slightly on demographic changes), while cooling energy demand will remain low (unless the amount of air conditioners strongly increases).

The Pilli-Sihvola, K. et al. (2010) econometric multivariate regression model for five countries in Europe found that the costs of energy demand of gradually warming climate on the need for heating and cooling will result in either a net gain or net loss, depending on weather variations. In Central and North Europe costs will decrease for users of electricity because the decrease in heating demand due to climate warming dominates. However, costs in Southern Europe will increase because the rise in cooling and electricity demand overcomes the decreased need for heating. The analysis undertaken by Mirasgedis, S. et al. (2006) indicates a net loss for the case of Greece. They found an increase of annual electricity demand in Greece due to climate change of 3.6–5.5%, with substantial increases during the summer period that outweighs moderate declines for the winter period. The increase in energy demand with strong annual variability will lead to the need for increases of installed capacity, a large percentage of which will be underutilized. Thus, appropriate adaptation strategies (e.g. new investments, interconnections with other power systems, energy saving programmes, etc.) need to be developed at the state level in order to ensure the security of energy supply. The total discounted costs of the overall energy system of Macedonia are estimated to approximately EUR 14.87 billion over the horizon 2006-2030. Climate change is expected to increase these costs by up to EUR 263 million – especially due to increased demand for air conditioning during hotter summers (Callaway et all, 2011). The annual total system costs due to impacts from climate change are expected to be up to 2.54 million by 2050 and up to 7.14 million by 2100 (Callaway et all, 2011a). Verica Taseska, Natasa Markovska, John M. Callaway (2012) found that the net benefits of adaptation in Macedonia were negative (EUR -1 M) in two cases (hotter in both winter and summer; colder in the winter and hotter in the summer) and positive (+2 M) in one case (colder in both winter and summer). In Cyprus, an expected rise in total (commercial and residential) electricity demand of about 6% is expected to cost between EUR 488 M and EUR 730 M (at today's prices using a 4% discount rate) up to 2050 (Zachariadis and Hadjinicolaou, 2014).

For the US economy and under the assumption of a one degree temperature rise by 2010, Rosenthal et al. (1995) reported a net reduction in energy consumption of $5.3 B. Contrary to that, GAO (2014) concluded that net electricity demand is projected to increase in every U.S. region and particularly in southern states. Mansur et al. (2005) estimated a net cost increase ranging from $4-9 B for 2050 and from $16-39.8 B for 2100, depending on the severity of climate change. Energy usage was predicted to decline up until 2014 but rise thereafter in Beecher and Kalmbach (2012). In the Midwest region of the US, increased demand associated with climate change could potentially exceed 10GW, which would require more than $6 billion in infrastructure investments (Beecher and Kalmbach, 2012). Under a 1.9ºC increase in mean state wide temperature, electricity requirements would increase from 2.6% and 3.7% in 2010. By 2099, the impact of climate change on annual electricity consumption will be in the range of 15%-30% of the baseline estimation or $15 to $30 billion (measured in 2006 USD). Net adaptation costs of US energy demand would range between $1.93 B to $12.79 B for the 2060 horizon (Morrison and Mendelsohn, 1999).

Looking at the commercial and residential sectors, Mansur, E.T., Mendelsohn, R and Morrison, W. (2007) reported a net increase in the demand for energy in residential and commercial sectors of the US by 2100 under different scenarios: under a 2.5º C warming scenario, total energy costs will increase by $57 B per year (38% to the commercial sector and 62% to the residential sector); under a 5º C warming scenario, total expenditures will increase by $26 B. The costs are greater in places with slightly higher temperatures, implying that a marginal uniform warming would lead to net damages in the US energy sector. The analysis suggests that average electricity prices will increase by 1.3¢ per kWh. The price increase will lead to a reduction in consumption of residential electricity of 89 billion kWh compared to the base case, implying a larger welfare loss of $0.6 billion. For commercial customers, consumption decreases 185 billion kWh compared to the base case leading to a reduction in the welfare loss of $1.2 billion. In warmer climates, both firms and households tend to choose electricity to heat and cool. When heating demand is low, consumers may find the low capital cost but high marginal cost of electricity relatively more attractive. This is an adaptation by residents and firms to warmer parts of the US. The Mendelshon, R and Morrison, W., N. (1999) theoretical–empirical model of the impact of climate change on the US energy sector predicted that the residential sector experiences damages in all climate scenarios in the year 2060 (from $2.4 B to $11.3 B) while the commercial sector experiences benefits (heating benefits dominate cooling damages) for the 1.5°C to 2.5°C scenarios. In the 2050 low climate scenario of a one-degree change, Mansur et al, (2005) predicted that residential expenditures (electricity demand) in the US would increase by 4 B$ while commercial expenditures would not change. By doubling the climate impacts in 2050 (from a one to a two degree change), the expenditures more than double (increasing to 9 B$). For 2100 and under a low climate scenario of 2.5°C, an increase in expenditures of $16 b is expected. Most of the increase is attributable to residential consumers. Finally, given a 5°C increase in temperature and a 15% increase in precipitation, total expenditures are predicted to increase by 40 B$. The analysis by Morrison, W. and Mendelson, R. (1998) indicates that the impacts (damages) of the change in the energy demand (cooling and heating) in the residential energy sector would range between $7 B (1.5°C scenario) and $26.6 B (5°C increase) in 2060. For the commercial energy sector, benefits (reduced costs) would range between $2.7 B (1.5°C scenario) and $2.1 B (above 2.5°C increase). By 2099, total US household electricity consumption could increase by up to 55% by the end of the century (Khanna, S., 2012).

The increase in energy demand in the US due to climate change will depend on the specific weather conditions. Excess energy demand is estimated to cost $59.2 B (1.4 discount rate) in the Southeast by 2100 in the business-as-usual case (Ackerman, A. and Stanton, E. A., 2008). The Southeast and Southwest states will face the highest net energy costs—after taking into consideration savings from lower heating bills. Total costs will add up to more than $200 B for extra electricity and new air conditioners, compared with almost $60 B in reduced heating costs. Overall estimations show that by 2100 in the business-as-usual case, climate change will increase the retail cost of electricity by $167 B, and will lead to $31 B more in annual purchases of air-conditioning units. At the same time, warmer conditions will lead to a reduction of $57 B in natural gas and heating oil expenditures.

In Los Angeles, the increased demands for cooling substantially outweigh the reductions from lower heating needs, particularly in a scenario with higher temperature increases. Peak demand could increase 19.5 percent above the 1961 to 1990 baseline by 2100 under a high emissions scenario (Vine, E., 2008). In Pennsylvania, New Jersey and Maryland a 2°C increase in temperature would result in energy consumption of 3.8% (Khanna, S., 2012). In Florida, the annual cost to generate power for extra air conditioning under a high-emissions scenario is projected to be $19 billion in 2100 (Stanton, E.A., and F. Ackerman, 2007). In California, analysts expect energy demand to rise 3–20 percent by the end of the century, primarily because of greater use of air conditioning. The added cost in energy bills could total $1 billion–$8 billion each year in today's dollars (Franco, G., and A.H. Sanstad, 2006). Additional needs for air conditioning during heat waves will cost New Mexico (USA) consumers 1.6 B$ per year by 2080 (Niemi, E. 2009a). The economic costs to the State of Washington energy system associated under a business-as-usual approach to climate change will be $222M/year in 2020, $623M/year in 2040, and $1.5M/year in 2080. Moreover, the additional costs related to the inefficient consumption of energy will be $1.4B/year in 2020, $1.6B/year in 2040, and $2.2B/year in 2080 (Adams, S., Hamilton, R., Vynne, S., and Doppelt, B. , 2010).

The total annual heating/cooling requirements of 5 star houses in five Australian cities are projected to vary in the range of -26% to +101% by 2050 and -48% to +350% by 2100 for the A1B, A1FI and 550 ppm stabilisation emission scenarios, dependent on the existing regional climate. In the regions with a heating/cooling balanced temperate climate such as Sydney, the increase in the total heating/cooling energy requirement is projected up to 120% and 530% for a 7 star house when the global temperature increases 2°C and 5°C respectively (Wang, X., Chen, D. and Ren, Z., 2010).

Future energy consumption in the Caribbean will increase as a result of climate change between 1.98 times (under SRES A2) and a factor of 1.35 (Under SRES B2) over the period 2013-2050 (Martin, R., Gomes, C., Alleyne, D., Willard, P., 2013). The assessed economic impacts ranged from US$ 487 billion to US$ 739 billion 2011 United States dollars during the forty years from 2013-2050, considering three discount rates (1 per cent, 4 per cent and 14 per cent) and two oil-price scenarios. If the Caribbean wants to focus on renewable energy sources, the region will need to invest US$ 27.6 billion. This will have co-benefits associated with the avoided costs from non-imported fuels. The economic impact estimates in ECLAC (2011) show that changes in electricity consumption as a result of climate change would have minimal economic impact in Trinidad and Tobago, that is, less than 0.1% of 2009 GDP for the 2011-2050 period under each of the A2 and B2 climate scenarios.

Results in Andre Frossard Pereira de Lucena, Roberto Schaeffer, Alexandre Salem Szklo (2010) show that the projected higher temperatures will increase electricity consumption in the residential and service sectors of Brazil by 6% and 5%, respectively. The power system should be dimensioned to generate additional 162 TWh and 153 TWh per year in the A2 and B2 scenarios. The necessary capital investments to build the projected increased capacity are 51 and 48 billion dollars in the A2 and B2 scenarios, respectively.

Electricity demand in Asia is growing rapidly. Isaac and van Vuuren (2009) estimate large increases in energy related cooling demand in Asia from climate change. According to the Asian Development Bank (2012), average increase of about 3.4% annually until 2030 is projected. This will require an investment of 3.3–4.6 T between 2006 and 2030; in the order of 160 B per year, of which about 87% will be needed in the developing member countries. Increases are projected to be especially high in India (AkpinarFerrand and Singh, 2010).

Recent adaptation studies have focused on alternatives to air conditioning. There are studies at national and local level on the costs of passive and retrofit options, particularly in Europe (e.g. van Ierland et al., 2006; Arup, 2008; ASC, 2011; Mima, Criqui and Watkiss, 2011). These include a range of options such as simple shading and orientation, design and building codes, and low- and very low-energy consumption buildings. While these apply primarily for new buildings, some also consider retrofitting of existing houses. These assessments find the benefits and costs to vary strongly across the range of climate projections, and with the assumptions underpinning the assessments. A general finding, however, is that it is more expensive to retrofit existing houses than to include these measures in new buildings. There are also challenges related to implementation (see Neufeld et al., 2010), which are likely to lead to policy costs. An alternative or complementary option is to reduce urban over-heating using spatial planning, such as green spaces and open plan development. There are some studies that look at the benefits of these schemes, though in the OECD context, the costs are very high, because of the costs of land-use change.

As well as over-heating, some recent studies have started to consider multiple urban risks and cross sectoral responses. For example, a study by Pohl et al. (2014) undertook a cost-benefit analysis of a set of adaptation options to a range of risks in a part of Rotterdam (the Netherlands), including heat, storm water flooding and drought, finding highest benefit to cost ratios for awareness raising and behavioural change. De Bruin, K. et al. (2009) estimated that to construct buildings with less need for air-conditioning and heating will cost €23,000 M. A particular option that has been advanced for such cross-sectoral studies has been green roofs, and a number of economic studies exist (van Ierland et al., 2006 in the Netherlands; LCCP, 2009 in London; Tröltzsch et al., 2012 in Düsseldorf; Nurmi et al., 2013, in Finland). These schemes offer multiple co-benefits (e.g. reduced energy, storm-water management, sewer overflow, air quality, urban heat island and greenhouse gases), though the literature often reports modest benefit to cost ratios.

Hallegatte, E., Hourcade, J. C. and Ambrosi, P. (2005) reported the following costs with perfect expectation: installing air conditioning in sensitive places will only need marginal investment in electric supply systems (S1 scenario); investment in electricity demand of €7 G and average operational cost of €400 M per year will be needed for installing Air Conditioning in almost all places (S2 scenario); upgrading building standards and making new ones less vulnerable will cost €1.2 G per year (S3 scenario); rehabilitation of existing apartments and building will cost €25,000 per apartment or 8 G€ total for Paris (S4 scenario). With Climate Change Uncertainty, the following measures and costs were reported: economic cost of adaption is null (BB scenario); total investment needed is €4 G per year plus € 1.2 G per year for upgrading buildings (BC scenario); rehabilitation of existing apartments should require €28 M per year over 65 years, making a total of €25 G (CC scenario); present Cordoba would be Paris climate over 2050: investments would be useless as investment costs are higher that global warming costs (CB scenario).

Additional energy needs in buildings can be alleviated to some extent during both winters and summers by increasing their energy efficiency. Evidence from the UK Department of Energy and Climate Change (2013) shows that energy efficiency policies deliver savings in energy demand and costs. For example, a total of 2.4 million wall cavities, 4.9 million lofts and 88,000 solid walls have been insulated through Government schemes since April 2008 and evidence shows that these measures can deliver significant savings – from £25 to £270 or more per installation per year. The average impact of policies is estimated to be a net saving of around 5%. New energy efficiency policies needed to reduce demand will cost $8 trillion each year up to 2035, specially needed in Europe, North America and China; mainly in transport and buildings (IEA, 2014).

Vulnerability of energy infrastructures

Energy infrastructures are vulnerable to climate change. The number of significant weather-related incidents to the electricity system has grown significantly since the mid-1990s: for example, from five in 1995 to 55 in 2006 (Vine, E., 2008). The costs are significant. For example, Hurricanes Katrina and Rita in 2005 destructed 115 platforms and damaged over 180 pipelines in the Caribbean Region, causing direct losses to the energy industry of over 15 B$, with substantial additional restoration and recovery costs (Contreras, R. and De Cuba, K., 2008; GAO, 2014). This led to dramatic impacts on the Caribbean and southern United States' energy production and distribution infrastructure, and ultimately on global energy prices.

Adaptation costs of energy infrastructures have been estimated. The World Bank Group (2010) has reported the following costs for Samoa in Africa: 0.01 million $/year for 2010-2019; 0.02 million $/y for 2020-29; 0.03 million $/y for 2030-39; and 0.06 million $/y for 2040-49. Measures to adapt include hardening—physical changes to make particular pieces of infrastructure less susceptible to storm related damage—or improving resiliency—increasing the ability to recover quickly from damage to facilities' components or to any of the external systems on which they depend.

Gross Domestic Product and electricity prices

Impacts on GDP have been assessed for Europe and Africa. Using a Computable general equilibrium model, Aaheim et al. (2012) concluded that impacts on GDP in the +2°C are moderate throughout Europe, with positive impacts in some sub-regions and negative impacts down to 0.1 per cent per year in others. At +4°C, GDP is negatively affected throughout Europe, and most substantially in the southern parts, where it falls by up to 0.7 per cent per year in some sub-regions. The authors also found that climate change causes differentiations in wages across Europe, which may cause migration from southern parts of Europe to northern parts.

Adaptation in terms of factor substitution within sectors.

Annual average GDP of the water and energy sector in Ghana will decline to within a range of $2.19 billion to $2.26 billion from a baseline output of $2.33 billion. In order to adapt, the country will need to diversify the energy mix. This will cost $84 million in 2012, rising to $113.6 million in 2040 and falling to $39 million in 2050. The cumulative total cost over this period is estimated to be $2.7 billion, and the average is estimated to be about $67 million per annum (World Bank Group, 2010).

Annual expected loss in Tanzania in the period 2008-2030 will range between -0.09% and -1.7% loss in GDP, depending on severity of climate change (ECA, 2009). Based on a cost-benefit analysis ECA estimated the cost-benefit ratios of different adaptation measures. The cost-benefit ratio of energy efficiency measures in the manufacturing industry is estimated at -0.08; Reduce gas pillage at hydro stations at 0; Gas CCGT (0.06); Solar PV (0.08); Targeted decrease of T&D losses (0.08); Coal (0.08); Solar conc. (0.08); Big hydro (0.08); Gas (GT) (0.09); Geothermal with T&D (0.09); Raising level of dam (0.12); emergency power (0.13); Small hydro with T&D (0.13); Biomass (0.16); Other decrease T&D losses (0.18); off-shore wind with T&D (0.26); Individual generator (0.35); Small hydro in Tanzania (0.44); Improve hydro turbine efficiency (0.51).

Electricity prices will change between 0 per cent and +1 per cent in 2030 and between -2 per cent and +3% per cent (generation and distribution costs and Taxes included), depending on the scenario (Dowling, P., 2013)

5.2 Health

5.2.1 Revision process

Climate change is expected to affect human health along direct and indirect pathways as a result of variations in air and sea temperatures, amount and frequency of precipitations, sea level rise and extreme weather events such as floods, storms, droughts, heat- and cold-waves. The burden of disease will depend also on a number of factors such as population health, access to the health care services, availability of safe water and sanitation systems, socio-economic and environmental conditions (Chiabai and Spadaro, 2014[1]). Though the highest burden is predictable in developing countries (due to the high population exposure and vulnerability, low health expenditures, lack of resources, weak institutional support and low adaptive capacity), health impacts are projected also in developed regions (Haines et al, 2006). The implementation of effective adaptation and mitigation measures has the potential of considerably reducing these impacts, and adaptive capacity can play a crucial role in this context. The successful planning of these measures in public health requires as a first step the correct identification and assessment of health impacts related to climate change in future scenarios. Against this background, the literature review is organized in two main parts, the first providing an overview of the main health impacts, while the second part focusing more specifically on adaptation. Table 2 presents the schema followed in the analysis of the literature. The health impacts and adaptation options analysed refer to heat waves, vector-borne diseases, food- and water-borne diseases. As regards heat waves, the adaptation options include building design, urban planning, early heat warning systems and emergency plans. For food- and water-borne diseases the options include surveillance and monitoring, microbiological risk assessment and technological solutions. For vector-borne diseases we mention again surveillance and monitoring, as well as vaccination and vector control systems. Diagnosis and treatment, and informational campaigns are common to all impacts.

---

[1] Published under BASE Project 7th FP (Bottom-Up Climate Adaptation Strategies Towards a Sustainable Europe).

Table 2. Literature review process: health impacts and adaptation options

CLIMATE IMPACT	ID	ADAPTATION MEASURES	DESCRIPTION
HEALTH			
Heatwaves	1	Building design (air conditioning)	Building design will perform a vital role in the future to cope with heatwave mortality (e.g., air conditioning systems, ventilation systems).
Heatwaves	2	Urban planning	Creation of open spaces or infrastructures, such as green areas, green roofs, etc. will provide a cooling effect against heatwaves.
Heatwaves	3	Early heat warning systems	Systems of warning and advice to the population have been implemented in most European countries after the heat wave occurred in France in 2003. They include preventive as well as reactive measures.
Heatwaves	4	Emergency plans	These plans include medical assistance and domiciliary services for those affected by heatwaves, especially the elderly.
Food- or water-borne diseases	5	Surveillance and monitoring	Disease control include observation of outbreaks, control of transmission factors and prediction of disease spread.
Food- or water-borne diseases	6	Microbiological risk assessment	The objective is to identify how disease incidence in humans is influenced by factors such as food preparation, processing, storing, etc.
Food- or water-borne diseases	7	Technological solutions	Food sanitation and hygiene are solutions to keep food and water in good condition through the implementation of different technologies (e.g. refrigeration).
Vector-borne diseases	8	Vector control	Destruction of infection via insecticides, larval control, etc.
Vector-borne diseases	9	Vaccination	Necessary for future scenarios.
Vector-borne diseases	10	Surveillance and monitoring	Disease control include observation of outbreaks, control of transmission factors and prediction of disease spread.
ALL impacts	11	Diagnosis and treatment	Early detection and treatment of the disease (e.g. medicines, hospitalisation).
ALL impacts	12	Education and information	Campaigns to inform people about beneficial behaviour (e.g. clothing, drinking during high temperatures, washing hands and hygiene to prevent water-borne diseases).

Source: Own work.

A specific focus has been given to the European countries, but other regions have been also included for a more comprehensive analysis, due to the small number of studies available especially as regards adaptation. The database with the main results is organized by type of health outcome, with a total of 52 reviewed studies: heat waves (12 articles), vector-borne diseases (13 articles), food- and water-borne diseases (15 articles). An additional section includes studies where different health outcomes are assessed (12 articles).

In the next section we provide, first, a short discussion of the main health impacts presumed to affect European countries, taking into account their geographical distribution with the areas that are expected to be mostly concerned. Based on the literature, we also discuss the studies providing quantitative information on the impacts with a certain degree of certainty, as well as other studies examining overall trends with an attempt to provide some plausible predictions though no model assessment is available. In a second step, we comment on the studies assessing costs and benefits of adaptation measures, both in Europe and outside Europe.

5.2.2 Main findings

Overview of health impacts

In the European context, human health will be concerned through increased frequency and duration of extreme weather events (heat waves, floods, storms, etc.), as well as through increased temporal and geographical distribution of food- and vector-borne diseases. 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 pre-existing 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. Developing countries would be highly impacted, considering urban poor population, the lack of air conditioning and poorly adapted urban design. In Europe the countries mostly affected will be the Mediterranean regions, Southern and Central-Eastern countries. The negative impacts might be counterweighed by some beneficial effects from the reductions in cold-related impacts due to warming in Northern Europe (Watkiss and Hunt, 2012). There are estimates of the economic costs of heat related mortality in Europe (e.g. Watkiss et al., 2009; Kovats et al., 2011). Potentially high welfare costs are reported, though the size varies with the valuation metric used. Relatively small increases in death rates are expected by 2040 while higher increases are projected to occur by the end of the century. Higher temperatures – both average and heat extremes – will also affect building comfort and energy demand for heating and cooling. The adaptation options for these two risks are closely related.

There are a number of other potential health impacts from climate change, both direct and indirect, which include changes in air pollution and allergens; deaths, injuries and mental well-being from extreme events; food and vector-borne disease; effects from altered agricultural production and food insecurity. There are also risks related to health infrastructures and to occupational health. The quantification of future ground-level ozone is constrained by a great deal of uncertainty, while there seems to be synergistic effects between high temperature and air pollution observed during heat waves, though how this can influence human health is quite complex to detect. Increased ozone concentrations have been observed during summertime in Southern Europe, whereas Northern Europe and the Alps have seen a decrease of concentration rates (Menne and Ebi, 2006). As regards flooding, the most affected regions are in Northern and Western Europe as well as Northern Mediterranean countries, with increased risks of deaths, injuries and mental problems (anxiety and depression) related to the intensity of the flood. In relation to vector-borne diseases, the Asian tiger mosquito is vector present in Europe which can transmit dengue and chikungunya. Increase in population of this mosquito in Central and Western Europe due to climate change could lead to a small increase of dengue, but further research is required in this context (Menne and Ebi, 2006). A few cases of local transmission of malaria occur annually in Europe (in travellers), but re-establishment of malaria in Europe is unlikely due to appropriate public health care (Watkiss et al, 2009). Leishmaniasis is projected to slightly increase, however its expansion is constrained by the limited migration of sand-flies. The vector might increase in Central Europe to higher altitudes, while it may decrease in Southern Europe especially where the climate is hot and dry (EEA, 2012). Lyme disease is endemic in Europe and the highest incidence is observed in Central Europe. The disease could slightly increase with higher temperatures and for increased contacts of people with ticks during leisure time. Tick-borne encephalitis is also endemic in Europe, mainly present in Northern and Central countries, and could extend to higher altitudes and latitudes (Watkiss and Hunt, 2012). Higher frequency of floods and heavy rainfall may disrupt water treatment and sewage systems and contribute therefore to an increase in exposure to water-borne diseases (salmonellosis, campylobacter, cryptosporidium, norovirus, and vibrio). For salmonellosis, the largest increase is expected in UK, France, Switzerland and Baltic countries. The PESETA and ClimateCost projects have estimated an increase in the annual number of cases of salmonellosis under different climate scenarios. The use of rainwater might increase during droughts boosting the development of campylobacter in untreated run-off water with a consequent increase of the disease in animals and humans, especially in rural areas. Northern Europe seems to be the most exposed with risk of groundwater contamination.

Health adaptation

Heatwaves

The adaptation measures for heat waves considered in the literature review include early heat warning systems and emergency plans, building design (e.g. air conditioning) and urban planning (e.g. green infrastructures). 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. The existing literature on epidemiological studies refers to different indexes for temperature to define a heat wave (e.g. the 95th percentile of the maximum daily temperature, mean daily temperature, apparent temperature which takes into account relative humidity) (Linares et al., 2014). The lack of uniformity in the definition of a heat wave makes more difficult the comparison of results among different studies in different locations. This is an additional factor adding to the existing uncertainty in the assessment of costs and benefits of early warning systems. This lack of uniformity in the measurement of the climate variable as well as of the health outcome (mortality or morbidity by type of disease) makes it difficult to transfer results from the study site to a new policy site as well as to carry out an upscaling at a wider geographical area.

As regards the costs and benefits of HHWWS, only a few studies exist in the literature. There is ex post data on the costs of these schemes, e.g. in France (ONERC, 2009) and Europe (WHO, 2009), and there are studies that have assessed their costs and benefits in relation to current risks (Ebi et. al, 2004 for Philadelphia, USA) and for future climate change (e.g. Hunt and Watkiss, 2011 for London and Tröltzsch et al., 2012, in Germany).

These indicate that such systems are a low cost response for addressing early heat related mortality. 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). The heat warning systems may include public information and awareness, as well as use of social care networks. The benefits of such schemes have been estimated to be considerably higher than the costs. ONERC (2009) assessed the costs of the French National Heatwave Plan for year 2005 equal to approximately €741,000 (2004 Euros) (as a sum of operating cost equal to €454,000 and cost of preparing the system equal to €287,000). On the other side, the value of years of life lost was estimated around €500 million before the implementation of the plan (during the heat wave of 2003). In Ebi et al (2004) the benefits of HHWWS were around €468 million compared to a cost of the system of around $210,000 over three years (1995-1998). The existing studies on heat warning systems have been carried out for specific urban areas. Using existing estimates for the Value of a Statistical Life, Alberini and Chiabai (2007) estimate the benefits of adopting the HHWWS system in the city of Rome at around €134.47 M for one summer (2004 Euros), while the social costs associated to the heat wave in the absence of any adaptation strategy would reach €281 M for 2020.

These results indicate that HHWWSs are a cost-effective response (i.e. with high ratios of benefits to costs) though it is noted that the future annual costs of these schemes will rise as the systems are triggered more frequently with future climate change (though benefits will also increase). Both Ebi (2004) and Hunt & Watkiss (2011) demonstrate that under plausible climate scenarios the cost-benefit ratio is very high, as did the UBA (2012) study in Germany. According to Tröltzsch et al (2012), the expected avoided deaths associated with the implementation of a heat warning system in Hamburg are projected around 2.36 billion€ per year in the period 2071-2100, with avoided costs of hospitalization of 2.51 billion€ per year in the same period.

The IPCC (Smith, et al., 2014) reviewed studies on the effectiveness of heat wave early warning systems, reporting that most studies found fewer deaths during heat waves after implementation. The existing studies make reference to avoided mortality when addressing the effectiveness, while morbidity is more difficult to evaluate (Toloo et al, 2013). Ebi (2004) calculated that the HHWWS in Philadelphia could have avoided 2.6 lives per day among the elderly (over 65 years old). Fouillet et al (2008) compared observed and expected deaths in the 2006 heat wave in France and estimated that the implementation of the system saved around 4,400 deaths with an effectiveness of the system ranging from a minimum of 60% to a maximum of 76% (68% on average). When addressing the transfer from a study site to a policy site the effectiveness of the measure is another important issue, as it might vary depending on the services included, if only the warning to the population or also health care services related to emergency plans, especially for the elderly.

Even when putting in place a HHWWS, there are still residual deaths as the warning system cannot prevent the health risks totally. With climate change, additional adaptation to address heat-related mortality is therefore likely to be needed. The latter represent however more expensive options. As an example, Michelon et al., (2005) report that immediately following the summer 2003 heat wave, €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 (Tröltzsch et al., 2012). These responses – and others that are suggested around the built environment and spatial planning involve intervention from outside public health. In this context there are examples of cost-benefit analysis of green infrastructures which can provide multiple benefits, among which positive impacts on human health. The benefits on health are not only related to the decreased risk of heat stresses and associated mortality due to their cooling effect, but also to the improvement of air quality and cut of particulate matters, the improvement of water treatment, and the reduction of the risk of flooding. Other beneficial effects on health include the reduction of health inequalities (access to green areas promoting good health contributes to the reduction of socio-economic health inequalities), the promotion of active lifestyle (contributing to a decrease in obesity and survival of senior citizens), promotion of better community cohesion, and improvement of mental health (calming and restorative effects) (MartinezJuarez et al., 2015).

EPA has specified that green infrastructures can represent an effective response to many environmental challenges. For example the City of Lancaster (Pennsylvania) put in place a green infrastructure plan in 2011 and the benefits for water, energy, air quality and climate change were evaluated to be of around $5 million in addition to $120 million as avoided cost of grey infrastructures. The total marginal cost of the green infrastructure has been estimated around $77 million (EPA, 2011), which shows the cost effectiveness of the plan. Costs of implementation and maintenance will depend on the extension of the area (green roof, park, etc.), on the type of vegetation and type of structure (e.g. intensive or extensive green roofs have different characteristics in terms of weight, soil depth, plant species, nutrient, maintenance and irrigation requirements).

Other health risks

There are two global studies that provide estimates of health adaptation costs: UNFCCC, 2007, also in Ebi, 2008, and World Bank, 2010. Ebi (2008) estimated the costs of adaptation to diarrhoeal disease, malnutrition and malaria in terms of preventive/treatment costs under different mitigation scenarios, assuming no increase in population and no economic/technological development. 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 Chiabai (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 as 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; the cost of reducing deaths and injuries 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.

These sets of global estimates have been complemented by a further series of studies in developing countries that have estimated the cost of health interventions to meet near-term targets such as the Millennium 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 assessed 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 at national level, though the focus is on developing countries. For India, Chiabai et al (2010) report on adaptation costs for malaria, diarrhoea and malnutrition under different scenarios of development, which are in the range $171-46 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 in Kenya, 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 (2010) 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 (US$592,000 for cardio-respiratory impacts, US$ 31,000 for malaria, US$34,000 for dengue and US$3.3 million for gastro-enteritis in A2 scenario, using a discount rate of 1%).

In the near-term the most effective measures to reduce vulnerability in developing countries are programmes that implement and improve basic public health measures, such as the provision of clean water and sanitation, to secure essential health care including vaccination and child health services, to increase capacity for disaster preparedness and response, and alleviate poverty (IPCC, 2014). These have high benefit-cost ratios and there is a considerable literature on these 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, and 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 plants 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 were estimated to be at least SEK 5.5 billion for local authority water supplies and SEK 2 billion for private water supplies. Similarly, there is some evidence on the cost-effectiveness and cost-benefit analysis of vaccination programmes against tick borne disease (Hsia et al, 2002, Desjeux, GaloisyGuibal 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 troops 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 to 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 are 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.

From the literature review, we can highlight a number of factors which are important when trying to do an upscale or a transfer of estimates from one region to another. The studies reviewed reveal a lack of homogenization due to a number of factors, such as the definition of the health adaptation costs, the measurement of the health benefits with different metrics, the population coverage, temporal and geographical scale, climate scenarios, among others, which add further complications. In the health sector, an accurate transfer and upscaling should be based on an appropriate projection of the physical impact before dealing with the costs and benefits of the measure. The assessment of the health impacts are based on specific epidemiological functions which are defined for specific local factors and the transfer can be done only under some strict assumptions. For example in the case of heat waves a key factor in any upscaling would be the identification of the appropriate threshold temperature for the health impacts which varies in space and time (Meyer F et al., 2015, Deliverable 5.2 BASE Project FP7).

5.3 Agriculture

5.3.1 Revision process

Agriculture is a highly climate sensitive sector and climate change has the potential for a large number of possible risks (IPCC, 2014). It may impact directly and indirectly on crop production, value chains and trade, with potentially negative effects such as lower rainfall and increasing variability but also positive effects, for example CO2 fertilisation and extended growing seasons. There are also potential impacts from changes in extremes, and the range and prevalence of pests and disease. Similar issues also arise for horticulture, viticulture, industrial crops and livestock. While negative impacts on yield are projected for most crops in tropical and temperate regions above 2 °C, the earlier patterns are uncertain, and include potential gains as well as losses in yields, with strong variations between crops and across regions (Porter et al., 2014).

Together with changing temperature and precipitation patterns, healthy soil ecosystems are also vital to crop production, for only fertile soils provide clean waters and quality crops (Klik and Eitzinger, 2010). While there is a long tradition of soil conservation policies in the United States, the European Commission adopted the Soil Thematic Strategy[2] in 2006, recognising soil degradation to compromise climate change and biodiversity objectives. In fact, as a consequence of unsustainable land use European soils have been degraded for centuries at a higher rate than soil regeneration, adding a strain on future European food and fibre production (JRC and EEA, 2010).

Beyond temperature, rainfall variations and extremes that have been largely studied as main climate threats to agriculture yields in the climate change literature, sustainable soil management has been tackled by a new generation of adaptation assessments. Soil degradation and associated adaptation options have also been given a special focus within the ECONADAPT literature review.

There are a number of potential adaptation options to address the above mentioned risks (Ignaciuk and Mason-D’Croz, 2014). These include: changing planting dates, use of new varieties, diversification and sustainable soil and water management techniques. In fact, more recent studies have shifted to more immediate timescales and focused on a wider set of practical adaptation options. These are already implemented by farmers in some regions and have been divulged under the headlines of climate-smart and conservation agriculture, while some of these also result being low regret options (see also current Box 2). Despite very low uptake in Europe, there is a general consensus about the benefits of climate-smart agriculture in the stabilisation of crop yield in the context of climate variability and change, specifically conservation agriculture (Farooq and Siddique, 2015). The work undertaken within the ECONADAPT project extended the approach that focuses on immediate and practical options to address soil degradation and water scarcity concerns or both simultaneously. It looked at six specific agronomic practices: no-tillage related techniques, de-compaction of soils, efficient irrigation schemes including for example drip, sprinkler and deficit irrigation, buffer strips and small agroforestry, cover and catch crops and residue management (Table 3). Information was gathered from a final list of 26 documents, resulting from a literature review process including academic journals, project deliverables and grey literature.

---

[2] http://ec.europa.eu/environment/soil/index_en.htm (visited 20 October 2015).

Table 3. Selected impacts and adaptation measures in the agricultural sector within the ECONADAPT literature review

Physical Impact	ID	Adaptation Measure	Description
Soil erosion and degradation	1	No-tillage	No-tillage, also called zero tillage, direct sowing or non-inversion consists of sowing the crop directly into the soil as opposed to the commonly practiced ploughing or conventional tillage. Partly implemented no-tillage techniques are included under this category.
	2	De-compaction	De-compaction aims to provide soil spaces for better aeration, water and nutrient permeability where dense soils have been strangled by ploughing or no-till systems, livestock pressure or agriculture machine traffic.
Drought and water scarcity	3	Efficient irrigation schemes	Under this category, systems and options that respond to either of the following criteria separately or jointly are included: irrigation system performance, conveyance efficiency and the application efficiency. These are for example: drip, centre pivot and sprinkler irrigation systems, improved drainage, periodical wetting but also deficit irrigation.
Soil erosion/ degradation and drought/water scarcity	4	Buffer strips, agroforestry and local forest improvement	Buffer or filter strips are vegetated or forest areas that act as a protection against overland flow and erosion from agricultural fields and reduce run-off from reaching watercourses. Broader vegetated areas (agroforestry) are included in this category.
	5	Cover crops and catch crops	A cover crop is a temporary crop that is grown together with the main crop to provide protection for the soil and fertility to the establishment of plants. To this category we also include catch crops which are vegetative covers that are planted between main crop rotations.
	6	Residue Management	Crop residue management means maintaining a vegetated cover on 60% percent of the soil surface at planting.
	7	Other measures	Other measures found in the include for example: conversion from arable to grassland, application of exogenous organic matter, soil protection in forests, erosion control programs, high density planting, timeliness, land use change or crop variety.

The subsequent paragraphs provide an overview of economic assessments of adaptation in the agricultural sector at the macro scale along with approaches to micro level adaptation costs and benefits. In reality these are not straightforward to distinguish. Sometimes for example micro economic costs and benefits of adaptation options result of macroeconomic models, averaging and therefore homogenising results over larger scales, misrepresenting the rich variation of local circumstances. The review below however attempts to differentiate main findings from both a macroeconomic perspective and approaches to direct costs of adaptation to the farmer. New iterative management approaches are also briefly introduced.

5.3.2 Main findings

Information on the costs and benefits of adaptation measures in the agriculture sector varies significantly not least due to the uncertainty over future impacts. First results from the recent ECONADAPT review confirm these findings. Although the evidence base for economic adaptation information can be extended, important uncertainties related to economic estimations of adaptation options in the agriculture sector persist.

Macroeconomic approaches

OECD (2008) identified a good coverage of adaptation benefits for agriculture, from two sets of studies. The first were based on 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. The results can be used as part of or as an input to global models, which allow autonomous market adaptation from trade, taking account of the total impact of climate change rather than just the direct domestic impacts. These studies mostly focus on the benefits of farm adjustments shown to cancel out climate change impacts on yields, while costs are assumed to be low or non-existent. The second were based on econometric (Ricardian) analysis (e.g. Seo et al., 2009), to assess the relationship between climatic factors and land value or farm net revenues.

At the global level, a UNFCCC study (McCarl, 2007) estimated research, extension and irrigation costs for the agricultural sector at USD 14 billion per year globally by 2030, of which 50% was in developing countries. The International Food Policy Research Institute (IFPRI) (2009) – as part of the EACC study – used an agricultural supply and demand projection and a biophysical crop model to estimate agricultural productivity investments and adaptation costs. For developing countries, EACC (2010) estimated costs of USD 2.5-3 billion per year. These studies found lower crop yields with climate change, especially for irrigated and rain-fed wheat and irrigated rice. They also found low costs of adaptation explained by restored welfare through trade, with some regions and countries becoming major food importers.

A large number of similar adaptation studies have been undertaken in developing countries (see ECONADAPT [2015] for further information). As an example of the coverage across countries, these include crop modelling studies (in Bangladesh, Bolivia, Ethiopia, Ghana, Mozambique, Samoa and Viet Nam [World Bank, 2010b, c, d, e, f, g], India [Markandya and Mishra, 2010] and Brazil [Margulis and Dubeux, 2010]), as well as sector investment and financial flow analysis in Bangladesh, Colombia, Ecuador, the Gambia, Liberia, Namibia, Niger, Paraguay, Peru, Togo, Turkmenistan and Uruguay (UNDP, 2011).

New, more sophisticated national, regional and global assessments are also being undertaken, which 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 recursively dynamic partial equilibrium models), using these to explore climate change impacts and adaptation policies including consumer support policy (e.g. Mosnier et al., 2014, in four East Asian countries). Such studies highlight that looking only at crop yield projections in one region is inadequate to derive conclusions on climate change impacts and adaptation at a macroeconomic level. More recent studies have also factored in uncertainty and robustness to such global assessments and considered transformational adaptation (e.g. Leclère et al., 2014). They include 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.

Analysis of the earlier crop modelling impact-assessment based studies compared to more recent policy studies reveals some insights. Earlier studies focus on a narrow set of adaptation options, particularly irrigation and fertiliser use. These studies rarely consider constraints and they exclude cross-sectoral issues. Studies that consider such factors (e.g. Iglesias et al., 2012, for Europe) find either policy constraints (e.g. on fertiliser use) or higher costs (e.g. from increasing competition for water in areas of water scarcity) compared to earlier studies. They also have optimistic assumptions about the substitution of domestic production for international trade under climate change, ignoring the costs that would be borne by local farmers as part of this transition, as well as the externalities associated with potentially lower food security levels. Finally, most do not consider uncertainty, look into scenarios one at a time, and assume high capacity and future foresight at farm level.

Direct approaches at micro level

Recognising limitations of macroeconomic estimates, more recent studies have shifted to more immediate timescales focusing on a wider set of practical adaptation options and considering decision making under uncertainty. These include low-regret as well as climate smart adaptation practices, many of the latter mostly matching with the first (see also Box 2).

In developing countries, promising low-regret options include: climate information, agrometeorological information, seasonal forecasting and early warning, research and development, crop switching/planting and diversification (agronomic management), pest and disease management, including post-harvest losses, soil and water management, ecosystem based adaptation and insurance (Ranger and Garbett-Shiels, 2012; ECONADAPT, 2015). Many of these overlap with existing agricultural development strategies. While this raises some issues of attribution, in relation to the overlap with existing agricultural development, they do have high benefit to cost ratios and work best when implemented as portfolios, rather than as single solutions, as found by Di Falco and Veronesi (2012). Some countries have assessed and costed these options in sector adaptation plans (e.g. Government of Tanzania, 2014).

Much of the recent focus in the literature has been on climate-smart agriculture (FAO, 2013), which encompasses sustainable agricultural land management practices such as agroforestry, soil and water conservation, reduced or zero tillage, and use of cover crop. These options improve soil tilth, through better soil aeration, water infiltration and holding capacity, as well as nutrient supply and soil biodiversity. Benefits include reduced risks from rainfall variability and soil erosion, increased soil organic matter, soil fertility and productivity, as well as reduced greenhouse gas emissions by reduced soil emissions.

There has been analysis of the costs and benefits of climate-smart options. Examples include qualitative cost-benefit assessment of various options in Canada (British Columbia, 2013), as well as a cost-benefit analysis of conservative or low tillage in Germany (Tröltzsch et al., 2012), though the latter found modest ratios of benefits to cost. These options are particularly attractive in developing countries, due to the large benefits associated with rain-fed agriculture, and there are studies on their costs (McCarthy, Lipper and Branca, 2011), benefits (Branca, 2011) and cost-benefit analysis (e.g. Branca et al., 2012; ECA, 2009; Lunduka, 2013). These studies report high benefits for these options, reduced greenhouse gas emissions, and in some cases large co-benefits. However, McCarthy, Lipper and Branca (2011) highlight that there is a high variation in costs between sites, and also, that many of the adaptation options have high opportunity or transaction costs, since introduction involves labour and land costs as well as foregone crop income. These costs are a barrier to adoption of climate smart options, particularly in subsistence economies. Benefit to cost ratios also vary with discount rate (as does the rate of return), as some options take several years to establish benefits, while costs are immediate. Furthermore some of the benefits of these options (e.g. environmental improvements or greenhouse gas emission reductions) may not accrue to local farmers. These various issues highlight the need for planned support.

There has also been work to identify such options in the agricultural sector of OECD countries (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 spending on research and development. The recent analysis by the Intergovernmental Panel on Climate Change (IPCC) reported that some adaptation approaches such as cultivar adaptation and planting date adjustment in combination with other measures are on average more effective than irrigation and fertiliser optimisation (Porter et al., 2014). A study in Germany (Tröltzsch et al., 2012) found that crop switching was a promising adaptation option, with high benefit to cost ratios. 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. Notable studies include the early work in Australia (Howden et al., 2003), which highlighted the high benefit to cost ratios of research and development 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 identifies low cost adaptation strategies for early moderate changes in water availability, such as irrigation efficiency and water allocation management.

In the pipeline, there is also some evidence on adaptation costs and benefits for horticulture, viniculture, livestock, forestry and fisheries, including aquaculture. This literature is less developed, 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.

The ECONADAPT literature review had a specific focus on sustainable cropland management understood also as low-regret options at European farm level. First results provide evidence of unequal, fragmented and site specific adaptation costs and benefits at local scale, similar to results from developing countries (Branca et al., 2011)

All net present values (NPVs) for no-till and related practices were found to range from (-) 945 £/ha to 522 £/ha assessed for the UK, depending on the type of costs, time horizon and discount rates considered (Rickson et al., 2010). The negative NPV applies to zero-tillage under economic valuation of additional ecosystem services resulting from the practice, a 15 year time horizon and a 3.5% discount rate.

The same study finds relatively low but negative NPVs for subsoiling but other studies also report positive net present benefits from de-compaction measures such as low pressure tires or ploughing. For this category of measures NPVs range from (-) 120 £/ha to 838 €/ha.

In the efficiency irrigation category the highest net cost was found to be 2000 £/ha for drainage. Drip irrigation has been relatively well reported as being associated with high capital costs and negative NPVs. A study that applies to Morocco equally shows that drip irrigation is not beneficial to farmers unless capital investment is subsidised (Boughlala, 2013). In a study from the World Bank however, Sutton et al. (2013) report possible high net present values for irrigation related adaptation options in Albania. These range from a net cost of USD 7,665 for new irrigation systems in intermediate agro-ecological zones (AEZ) for irrigated alfalfa under low price scenarios, and net benefits of up to USD 197,691 for irrigation water systems for irrigated maize in northern AEZ, under a high price scenario by 2050. The same authors study equal adaptation options for Macedonia, Former Republic of Yugoslavia and Moldova.

For the buffer strip category NPVs range from (-) 398 to 781 £/ha, the first case corresponding to in field buffer strips and the second for agroforestry measures. However, this range is not representative for net costs. For example, agroforestry measures can also provide negative present values such as shown by data ranges from Canada (Trenholm et al., 2013).

Rickson et al. (2010) also provide negative net present values for cover crops up to (-) 3067 £/ha but evidence exists for positive net present benefits up to 2034 €/ha if low operation costs and high benefits of the measure are considered.

These authors (2010) also assess the NPV of other farming techniques. Their NPVs range between (-) 4657 £/ha for land use change or (-) 3524 £/ha for crop rotation to 300 £/ha for high density planting. Benefits of 3240 €/ha are also reported in Germany for the transformation of cultivation across slope gradients to permanent grasslands.

In the reviewed literature, cost efficiency metrics (CE) are often used to assess the relative costs of different options aimed at a same specific objective. Results therefore depend primarily on the objective of the measure, for example emission of carbon equivalent avoided, cubic meters of water saved, percentage of risk reduction or soil pressure reduction in terms of bar reduced. In general, these studies use approximate costs of measures as input data to run models and calculate cost efficiencies. Although micro level costs are not always comprehensive, more macro-level data can be derived at regional or national levels from cost efficiency ratios, where potentials to reach set objectives are available. In that case, cost metrics cannot be given in a per hectare basis but in total costs for the total area, where measures can be applied.

For no-tillage techniques cost effectiveness figures range from (-) 9904 to 9107 €/tCO$_2$e in Scotland and for potatoes under high and low yield effectiveness respectively (McVittie et al., 2014). Generally low yield effectiveness provide positive CEs while high yield effectiveness provide negative costs of no-tillage if looked at from the perspective of reducing carbon emissions.

For land drainage as part of the measures to reduce water shortage, MacLeod et al. (2010) assess CEs of 43 to 46 £/tCO$_2$e. Instead, Rodrigues et al. (2013) look at the relative cost of water savings from different innovative irrigation schemes and under four different irrigation timings including deficit irrigation in Portugal where CEs range between (-) 0,26 to 0.74 €/m^3.

For buffer strips, cost efficiencies of between 2.3 and 86.2 €/t of eroded soil avoided are reported in Germany. Results depend on the erosion rate of the site as well as on the extensiveness and width of the buffers. Another study looks into the cost of pesticide risk reduction in Germany and comes up with cost efficiencies of riparian buffer strips resulting from conversion of agricultural land (Sieber et al., 2010). Results vary from between €332 per percentage of risk reduction for 3m wide buffers in the Saarland region and €872,000 per percentage of risk reduction in Lower Saxony for 50m wide buffers.

For cover crops, cost efficiencies have been found in terms of carbon emissions avoided. McVittie et al. (2014) reports CEs between (-) 1522 and 2308 €/tCO$_2$e for potatoes and maize and differences in yield effectiveness respectively.

The same authors also find cost effectiveness figures for residue management ranging from (-) 2 €/tCO$_2$e in Poland to 1359 €/tCO$_2$e in Spain. The high cost in Spain results even under high yield impact of residue management applied to irrigated wheat, while the cost in Poland are low, even under low impact on yields and for various crops.

For other measures cost effectiveness was found to be between 6 €/t to 18 €/t of eroded soil avoided in Germany from erosion control programs or between 16 and 30 €/t for transformation of cultivation on sloping land to permanent grassland under specific crop rotations. Finally, MacLeod et al. (2010) and McVittie et al. (2014) find cost effectiveness figures ranging between (-) 905 to 4434 €/tCO_2e, the first applying to use of manure for fertilization and the second to adopting systems less reliant on inputs.

Two main features result from the ECONADAPT analysis: firstly, if adaptation options can drive advantages, cost of adaptation to farmers do appear to be positive in many cases and cannot be discarded or considered non-existent, even if they can be cancelled out in the longer run or at global levels. Secondly, results appear to vary in sign and magnitude which typically depends on local circumstances. Some authors emphasise the importance of local assessments, average figures misrepresenting actual impacts. An illustrative example shows how net economic advantages and interests can diverge among farmers even within a small scale river basin. Some studies also inform about the non prescriptive nature of their analysis even in case adaptation options result economically advantageous (Sutton et al., 2013). Indeed, due to the complex nature of this kind of analysis, it is therefore also but a short step from adaptation to maladaptation, one same adaptation option turning to maladaptation depending on the context.

Iterative management approaches

Finally, there are some studies that consider and cost agricultural options using iterative adaptive management planning (e.g. Downing et al., 2011; Matiya, Lunduka and Sikwese, 2011). Examples from the agricultural sector also include the United Kingdom study on the Economics of Climate Resilience (Frontier Economics, 2013) which developed adaptation pathways (roadmaps) for the sector. This identified early options that focused on building the enabling environment and information for adaptation in the farming sector, rather than technical options. Further examples include the application of iterative management in the Ethiopian Climate Resilience Strategy (FRDE, 2014) and real options analysis to agricultural irrigation in Mexico (World Bank, 2009).

5.4 Infrastructure

5.4.1 Revision process

Infrastructure is a cross-cutting sector and has been considered systematically in the other sections (e.g. energy infrastructure). Here, the focus is on overall estimates, as well as specifically on transport and other critical (not considered in other sections) infrastructure. Table 4 presents the schema followed in the analysis of the literature. Impacts analysed include heat waves, flooding and storms (including strong winds). Adaptation options include heat-resistant road cover, adaptation of rail infrastructure to heat and temperature change and retrofitting airports against heat (to deal with heat waves); retrofitting existing road infrastructure concerning increased precipitation, retrofitting airports against higher precipitation, improvement of water flow management, and flood protection for strategic buildings (to deal with flood risk); adaptation of shipping fleet for rivers (to deal with droughts) and retrofitting existing infrastructure of shipping, adjustments of maintenance of rail infrastructures, vegetation management along roads and rails and Weather Information System (to deal with multiple risks). The ECONADAPT literature database was searched for relevant studies on impacts and adaptation to (transport) infrastructure. This resulted in the consideration of 29 relevant publications which shows the limited number of research into the impacts of climate change on infrastructure in general and transport infrastructure specifically.

5.4.2 Main findings

The impacts of climate change on infrastructure are multiple. The following presents results regarding the cost of adapting to impacts. Benefits generally refer to the avoid costs of climate change impacts.

UBA (2012) estimated the additional costs of establishing heat-resistant roads and rail networks for Germany to respectively 10 - 40 million Euro and 25-60 million Euro per year which would result in 3675 million Euro and 35-64 million Euro per year in benefits. At EU level, Altvater et al. (2012) examined the retrofitting of road, rail and airport infrastructure to increased temperature, resulting in respectively 3-6 billion Euro, 58-261 million Euro and 143-428 million Euro per year, with benefits of 2-2.6 billion Euro, 89-537 million Euro and 143-428 million Euro per year.

Table 4. Analysis of the literature: main impacts and adaptation measures.

Climate impact	Adaptation measures	Description
Heat waves	Heat-resistant road cover	Extreme heat but also greater temperature variability will put a larger strain on road pavements, leading to cracks, rot occurrence or pavement blow-ups. These pose additional risks to transport users. New construction materials can be used to cope with these effects and to make pavement more heat resistant (e.g. new, heat-resistant paving materials, more common use of polymer-modified bitumen, improvement in pavement technology, using polymeric grids to avoid rutting, using materials on the surface which reflect solar radiation).
	Adaptation of rail infrastructure to heat and temperature change	Extreme heat may lead to rail buckling. During extreme temperatures, trains would have to run slower or would face the risk of derailment. Adapting the rail system to cope with great temperature variability will include an adjustment of the stress free temperature or even the use of other steel types. Stressing is a technique to avert track problems such as fracturing or buckling at the temperature extremes. Stress free temperature is 75% of the expected maximum temperature of the region and should be adjusted to increasing temperature, so that stressing is not necessary.
	Retrofitting airports against heat	Extreme heat but also greater temperature variability will put a larger strain on airport runways, leading to cracks, rot occurrence or pavement blow-ups. These pose additional risks to outgoing or incoming planes. New construction materials can be used to cope with these effects and to make pavement more heat resistant (e.g. new, heat-resistant paving materials, more common use of polymer-modified bitumen, improvement in pavement technology, using polymeric grids to avoid rutting, using materials on the surface which reflect solar radiation).
Flooding	Retrofitting existing road infrastructure concerning increased precipitation	Damages from flash floods and extreme precipitation events can be avoided through proper and scheduled maintenance of drainage. In some regions, where intensive precipitations are likely to increase, an upgrading of drainage should be considered.
	Retrofitting airports against higher precipitation	Damages from flash floods and extreme precipitation events can be avoided through proper and scheduled maintenance of drainage of airport runways. In some regions, where intensive precipitations are likely to increase, an upgrading of drainage for airport runways should be considered.
	Improvement of water flow management	Installation of flood gates. The option protects against flooding, especially river flooding, and can help to secure sufficient water level for shipping. Furthermore, flood gates can combine the accessibility of larger harbour and flood protection.
	Flood protection for buildings	A railway system also needs buildings such as railway stations and control centres. In case of flooding these buildings are a weak point in the system especially if electronic equipment is placed in such buildings. Even a small amount of water can destroy electronic equipment and this can lead to the closure of tracks although the track itself is not damaged by the event. Flood protection measures for these buildings are essential to protect such buildings (especially the control centres). These can be achieved by pile construction, mobile flood gates, move of all relevant equipment in the upper floors, etc.
Drought	Adapt shipping fleet for rivers	For drought situations at rivers, adjustments at the shipping fleet are a possibility. Different alternatives are: other lighter materials, new boat designs, etc.
Multiple risks	Retrofitting existing infrastructure of shipping concerning extreme events	Several options can be used to ensure stable conditions for inland water transport, especially a stable river-bed. For example, river groynes are rigid hydraulic structures built from an ocean shore (in coastal engineering) or from a bank (in rivers) that interrupt water flow, limits the movement of sediment and protects coastal areas or river banks. The option can protect against flood, but also droughts.
	Adjustments of maintenance of rail infrastructures	Maintenance includes many different possibilities to reduce infrastructure vulnerability that is caused by infrastructure in poor condition. Some examples: Maintenance of rail track (including replacement in time) reduces rail buckling during heat periods. Maintenance of embankments and drains guarantees the functioning of these systems if heavy rains or floods occur. Frequent inspection of bridges (especially corrosion) reduces damage and destruction risk due to heavy rains
	Vegetation management along roads and rails	Due to the increasing intensity and quantity of extreme events, especially storms, vegetation management along roads and rail tracks should be adjusted. Vegetation management along roads and railways can reduce the risks of interruptions to transport infrastructure (roadsides/rail tracks). Possibilities are cutting down of trees that may fall during extreme storms and pose risks, choosing the proper vegetation for changing climatic conditions, planting of vegetation, protection forest to stabilize soil along roadsides/rail tracks and to prevent the risk from mudslides and erosion.
	Weather Information System	Information on weather is already used in the logistics sector. This is mainly short- and mid-term information. Due to climate change, especially effects of extreme events, weather information will become more important for logistical processes. The resulting information needs to be improved and refined.

Altvater et al. (2012) estimated the cost at EU level of retrofitting existing road infrastructure to increased precipitation through improved drainage system to 49 - 243 million Euro per year with benefits of 19 -57 million Euro per year. Upgrading of airport infrastructure drainage system was estimated at 36 - 182 million Euro per year. In Australia, the construction of levee gates to protect sections of the railway tracks against flooding cost 100,000 AUS $ (Natural Disasters in Australia, 2002). Automatic monitoring and protection system to prevent damage from flooding of control centres for the railway network was estimated at €30,000 per 100km on average (Doll et al., 2011). This is a similar cost to other studies (Maurer et al., 2012).

Protecting fluvial and maritime transport infrastructure can be very expensive. For example, the construction in 1997 of the barrier Maeslantkering‖ (which is part of the Europort gate system of Rotterdam) cost 450 million euro (Doll et al., 2011). The movable barrier is made of two 22 m high and 210 m wide doors – two floating pontoons which automatically close when a threatening water level is approached (i.e. 3 m above average sea level). Still in the Netherlands, the construction of the Oosterschelde barrier cost 2.5 billion Euro with €17 million per year operation costs (Doll et al., 2011). Other European examples include the Italian MOSE plan (Modulo Sperimentale Elettromeccanico) to protect Venice from flooding from exceptional high tides. The plan involves the construction of 79 mobile underwater giant steel gates at three lagoon inlets which will take approximately eight years to be built and cost $2.6 billion (Doll et al., 2011). The construction cost of the London flood gates was around £534 m (£1.3 billion at 2001 prices) with an additional £100 m for river defences (Doll et al., 2011).

One study was found on adapting shipping to more frequent droughts. The strategy proposed was to change the materials used in shipbuilding to fibreglass and reinforced plastic. The lighter material means that ships can operate at lower water level, require less fuel, carry more goods, and can run at a higher speed. The estimated cost is at 12-13 Euro per kg/fibreglass (compared to 2-4 EUR/kg for a regular steel inland ship).

Several studies examine the benefits of improving weather services for securing transport. Altvater et al. (2012) calculated the cost of installing additional hydrological stations in Europe to improve weather forecast across Europe at 23 million Euro (investment cost) and 2.9 million Euro per year (maintenance costs). The UBA (2012) calculated the cost of providing better weather services for the transport sector at 4.3 to 8.6 million per year for Germany, with benefits of 3.8 million Euro per year. The limited net benefits obtained in this study however contradicts Pilli-Sihvola et al. (1997) and Bosello's (2001) earlier finding that the benefit:cost ratio was very favourable (both studies find a B:C ratio of 5 respectively at US and EU levels). Wass (1990) and WTI (2009) also finds significant benefit in investing in weather forecasting for transport for the EU and US while Lähesmaa (1997) finds a low B:C ratio for Finland. Differences are probably due to a range of factors, from the scale examined, the level of past investment in weather forecasting, the density of traffic, and the significance of weather events for transport.

A number of studies also investigated the worth of using protective vegetation against multiple climate related risks (i.e. avalanches, rock fall, landslides, soil erosion, flooding). Doll et al. (2011) found that adequate forest management cost about EUR 100/ha at EU level, while the re-cultivation of damaged protection forest needs an investment of about EUR 50.000/ha (in addition to costs incurred to infrastructure). A similar valuation was achieved by BUND (2011) which suggests 2000 Euro per ha in maintenance cost every 20 years, compared to 50,000 Euro per ha for restoration costs and 500,000 Euro per ha for technical avalanche protection.

At the global level, these were estimated using an investment and financial flow analysis in the UNFCCC study (2007), which estimated very high costs. Subsequently the World Bank's EACC study (2010) used an impact assessment method for adjustments in building standards for changing average temperature and precipitation, estimating infrastructure costs for developing countries at USD 13.5-27 billion per year in the period 2010-50, over half of which was for urban infrastructure.

There are some estimates of the additional cost of adaptation for transport infrastructure, including road and rail (Jochem and Schade, 2009; SCCV, 2007, in Sweden; Tröltzsch et al., 2012, in Germany). Recent studies in the United Kingdom indicate many of these risks can be addressed at low cost as part of planned maintenance and refurbishment regimes (Atkins, 2013) though high costs may be associated with strengthening bridges vulnerable to climate change (see Wright et al., 2012, in the United States). There have also been adaptation cost studies on road infrastructure in developing countries, including in Ethiopia and Ghana (World Bank, 2010).

In relation to colder regions, the costs of adaptation for infrastructure were considered for Alaska by Larsen et al. (2008), which reported that infrastructure costs could increase by as much as 10-20% in present value terms (USD 3.9-6.6 billion for the period 2006-30). Interestingly, adaptation in this study was understood as a more frequent maintenance and replacement schedule of infrastructure. Similarly, a cost study by Zhou et al. (2007) examines the infrastructure costs in the Northwest Territories of Canada. A number of studies have also considered the potential costs of adaptation of non-tropical windstorms, including Hunt and Anneboina (2011) in Europe, Tröltzsch et al. (2012) in Germany and SCCV (2007) in Sweden.

In recent years, the focus has moved towards climate risk screening for new infrastructure, as retrofitting of infrastructure is often expensive. By identifying risks at the outset, it is possible to avoid locating infrastructure in areas that are exposed to current or future climate risks. The consideration of future risks can also be used to change design, for instance, to build-in higher protection levels, increase flexibility or to allow more robustness. All these responses can build resilience to future risks. However, these can incur higher upfront costs, which need to be weighed against the expected benefits: As an example, the World Bank (2006) estimated that accounting for future climate in high-risk projects today could potentially increase project costs by 5-15%. While this may be justified for critical infrastructure (water supply, and health and emergency), it may not be justified in all cases, especially given the timing (and uncertainty) of future benefits and the (economic) lifetime of investments.

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, overdesign 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 resilient 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 overdesign). 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.

5.5 Coastal zones and sea level rise

There are a number of risks from climate change on coastal zones, including not only sea level rise, but also storm surges and wind-storms, flooding, loss of land, coastal erosion, salt water intrusion and impacts on coastal wetlands. In response, there is a broad set of adaptation options – generally based around protection, retreat or accommodation (IPCC, 2007). There is a comprehensive evidence base on these costs and benefits (OECD, 2008), and this has increased further in recent years.

5.5.1 Main findings

A large number of studies have used sector impact assessment models to assess adaptation costs and benefits, many using the Dynamic Interactive Vulnerability Assessment (DIVA) model, which assesses the costs of physical barriers (dikes) to address flood risks and shoreline management (beach nourishment) to address coastal erosion (Hinkel and Klein, 2009). DIVA has been used for global studies (UNFCCC, 2007; World Bank, 2011), regional studies (e.g. in Africa [Brown et al., 2009] and Europe [Hinkel et al., 2010]) and national studies (e.g. for individual European countries [Brown et al., 2011] and in Mozambique [World Bank, 2010b]; Ghana [World Bank, 2010c]; Kenya [SEI, 2009]; Peru [IBD/ECLAC, 2014]; Tanzania [GCAP, 2011]; and India [Markandya and Mishra, 2010]). The most recent runs of the model suggests that estimated global annual investment and maintenance costs of protecting the coast to 2100 are in the range of USD 12-31 billion to USD 27-71 billion for low and high warming scenarios (Hinkel et al., 2014). The additional adaptation costs associated with coastal erosion (beach and shore nourishment) are estimated at a further USD 1.4-5.3 billion per year across low, mid and high scenarios (Hinkel et al., 2013).

Similar types of impact assessment studies have been undertaken in a number of countries, including Canada (Stanton, Davis and Fencl, 2010), Brazil (Margulis and Dubeux, 2010), the United Kingdom (Evans et al., 2004), the United States (Neumann et al., 2011), Germany (Tröltzsch et al., 2012); and there are also similar studies at local level. All of these studies find that coastal adaptation reduces damages significantly at relatively low cost and leaves low residual damages: it thus has high benefit to cost ratios, which generally increase throughout the 21st century. Annual adaptation costs are also generally a low proportion of GDP: For example, Agrawala et al. (2011b) estimated that it accounts for less than 0.1% of GDP though this does vary with country and region.

The cost estimates, however, tend to exclude adaptation costs linked to wind storm damage, salinization, port infrastructure, tourism, coastal and marine ecosystems, and often dike maintenance costs. These estimates also often assume good levels of existing protection and no adaptation deficit (Brown et al., 2011) – the latter a key issue for developing countries. There are some studies that address these gaps. The World Bank's EACC study (2010) estimated that costs were modest (USD 0.20.5 billion) when compared to the costs of sea defences. Local studies also emerging (e.g. the IFC (2011) report on the port of Cartagena, Colombia) that address some of these issues. Similarly, studies have assessed the adaptation costs for tropical windstorm damage under climate change, including in

Florida (e.g. RMS, 2009), the Caribbean (ECA, 2009; CCRIF, 2010) and Samoa (World Bank, 2009c). Nonetheless, the coverage of adaptation costs is still partial.

There are also coastal studies that are more policy focused. These reveal some new insights when compared to the impact assessment (I-A) studies described above. First, estimates of coastal adaptation costs and benefits vary with the level of protection (the objective). Earlier studies assume modest protection levels that are below existing standards in some OECD countries (e.g. the Netherlands), and in some cities (e.g. in London). In such cases, maintaining current protection levels will lead to higher adaptation costs. Second, I-A studies assume foresight – the models are run for one scenario at a time – and thus do not consider uncertainty. Related to this, studies that consider more extreme sea level rise (i.e. projections of 1 metre or more) report sharp increases in damage and adaptation costs (e.g. globally [Vafeidis et al., 2011] and in Europe [Brown et al., 2011]). Third, major cities may face much higher adaptation costs, especially for port-river cities which require highly engineered protection. As an example, the costs of protecting London against future sea level rise may require the construction of an additional flood barrier later this century (under a high sea-level rise scenario), which could cost GBP 6-7 billion (EA, 2009; EA, 2011). Hallegatte et al. (2013) analysed 136 global coastal cities and reported indicative adaptation costs of USD 350 million per year per city, or approximately USD 50 billion per year in total. Finally, I-A studies assume highly effective adaptation and ignore the costs of developing and implementing policies. Emerging policy studies in the Netherlands and United Kingdom (discussed above) indicate national adaptation costs that are many times higher than the impact assessment studies for the same countries (e.g. compared to Brown et al., 2011) for the various reasons above, i.e. higher risk protection levels, the consideration of uncertainty, more complex adaptation responses and policy costs.

While these earlier impact assessment studies provide critical information and context, recent studies have moved towards the analysis of early low-regret (see Box 3.2) and iterative adaptation. A number of these draws on existing disaster risk management and soft or non-technical options. Promising early low-regret options include (Mechler, 2012; ECONADAPT, 2015):

- Climate services, forecasting and early warning systems: These have high benefit to cost ratios (World Bank, 2011), as shown by example in the United States on hurricane risk (Lazo, Rice and Hagenstad, 2010; Lazo and Waldman, 2011; Considine et al., 2004) and in developing countries (e.g. Bangladesh [Paul, 2009] and South-East Asia [Subbiah, Bildan and Narasimhan, 2008]). Benefits generally increase under climate change (ECA, 2009) though this depends on the risk.

- Disaster risk management and emergency/contingency plans: This includes forums/ institutional strengthening, awareness raising, response plans and emergency infrastructure including shelters and rescue centres. These measures have high benefit to cost ratios for current risks and future climate change (e.g. Cartwright et al., 2013 in Durban).

- Natural coastal buffer zones: These include mangrove conservation, replanting and restoration, and similar measures for seagrass and coral, as well as shoreline restoration and marine protection sites.

  Such ecosystem based measures have been prioritised (with high benefit to cost ratios) in many studies, (e.g. in Samoa [ECA, 2009] and the Caribbean [CCRIF, 2010]). However, in high income countries, the costs of mangrove restoration can be very high (e.g. in the United States [World Bank, 2011]) and there are potential opportunity (land) or policy (enforcement) costs.

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

The list of low-regret options above have upfront benefits – and provide enhanced resilience for the future – though on their own, they may not be sufficient to address more extreme risks from longer term change (see World Bank, 2011). There are also a set of responses that build early resilience to longer term change, though these tend to involve more site specificity and thus their low-regret characteristic varies. Examples include:

- Climate risk screening: When applied to major infrastructure developments, climate risk screening can be used to consider location and design and has been found to have high cost-effectiveness if included at the design stage, because of the avoided reconstruction costs from floods and storms (e.g. ADB [2005] in Micronesia and Cook Islands). The siting of critical infrastructure such as hospitals and water treatment facilities away from high risk areas is also a low regret option. In some cases, a degree of over-design to higher protection levels is justified, because of their importance following a disaster (World Bank, 2011).

- Land-use planning and set-back zones: Some studies report that coastal zoning or back away areas or lines (where development is prohibited) have high benefit to cost ratios for hurricane protection under current climate variability and future climate change (e.g. in the Caribbean [CCRIF, 2010] and in Samoa [ECA, 2009]) and storm-surge (Cartwright et al., 2013 in Durban). However, in middle income and OECD countries, these involve high opportunity costs of land.

- Building codes: While building codes are often cited as a potential low-regret option (e.g. IPCC, 2012), the picture varies. Some studies find high benefits (e.g. in Florida [ECA, 2009] and in Samoa [World Bank, 2010]), but others report low benefit to cost ratios (e.g. in the Caribbean [CCRIF, 2010; Hochrainer-Stigler et al., 2011]) due to differences in risk levels, the costs of resilience, existing cost and asset life-time, and assumed discount rates.

In OECD countries, there is increasing interest in alternatives to engineered coastal defences. There are studies that assess the costs and benefits of spatial planning options (see de Bruin et al., 2014). 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 approaches have potential advantages, providing co-benefits and flexibility against future uncertainty. A number of studies have assessed their costs and benefits. A cost-benefit assessment of salt marshes in the Netherlands found that ecosystem-based approaches were less expensive than traditional options over the longer term (net present value) and in terms of construction costs, but that they were more expensive in terms of management and maintenance costs alone (De Bel, Schomaker and van Herpen, 2011).

De Bruin et al. (2012) looked at future sea level rise in the Netherlands and compared sand dunes against hard structural protection: Sand dunes offered greater flexibility and lower capital costs, but maintenance costs were higher. The choice of discount rate is therefore critical in choosing between these options. There are also recent studies that have assessed flood management strategies under climate change, comparing low-regret and green alternatives against large-scale flood protection infrastructure. Examples include the analysis of flood management New York in the United States (Aerts et al., 2013; Aerts et al., 2015), which compared wetland restoration and increased building codes and recommended a hybrid solution, combining protection of critical infrastructure and resilience measures that could be upgraded over time, at least in the medium term.

Box 2. What are low- and no-regret adaptation options?

Numerous studies recommend that no- and low-regret actions are a good starting point for early adaptation, as they offer benefits now and lay the foundation for future resilience (UKCIP, 2006; Watkiss and Hunt, 2011; Ranger and Garbett-Shiels, 2012; IPCC SREX, 2012). No-regret adaptation is defined (in the IPCC glossary) as adaptation policies, plans or options that "generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs". This includes 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 similar to development. There is, however, no agreed definition of low-regret options, and definitions include: i) options that are no-regret in nature, but have opportunity, transaction or policy costs; ii) options that have benefits (or co-benefits) that are difficult to monetise; iii) low cost measures that can provide high benefits if future climate change emerges; iv) options that are robust or flexible, and thus help with future uncertainty. DFID (2014) – and this report – uses a pragmatic definition of "low-regret" – that focuses on promising options for early adaptation. 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: UKCIP (UK Climate Impacts Programme) (2006), Identifying adaptation options, UKCIP, London; Watkiss, P. and A. Hunt (2011); Method for the UK Adaptation Economic Assessment (Economics of Climate Resilience), Final Report to Defra, May 2011. Deliverable 2.2.1; Ranger. N. and S.-L. Garbett-Shiels (2011), How can decision-makers in developing countries incorporate uncertainty about future climate risks into existing planning and policy-making processes?, Policy Paper, Grantham Research Institute on Climate Change and the Environment, London; IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York; DFID (2014), Early Value for-Money Adaptation: Delivering VfM Adaptation using Iterative Frameworks and Low-Regret Options, DFID, London.

Finally, a number of OECD countries are adopting adaptive management, looking at the overall adaptation pathway, from short- to long-term responses. In the Netherlands the Delta programme has advanced short-term measures that increase adaptability (flexibility) and resistance to extreme events (robustness), and delay tipping points. Most recently, the programme has moved to dynamic adaptation pathways (Delta Programme, 2014) and dynamic cost-benefit analysis (Kind, 2014; Eijgenraam et al., 2014). Similarly, the Thames Estuary 2100 project used an iterative approach to consider future protection for London, considering a portfolio of options linked to enhanced monitoring (EA, 2009; EA, 2011). There are also a number of studies that have applied decision making under uncertainty tools (see Chapter 6), including the use of real options analysis for dike heightening in the Netherlands (van der Pol et al., 2013), an analysis of hard infrastructure, restoration of mangroves and coastal zone management options in Mexico (Scandizzo, 2011) and the value of maintaining flexibility for engineered structures in Greece (Kontogianni et al., 2013), and an application of robust decision making for planning coastal resilience for Louisiana in the United States (Groves and Sharon, 2013).

5.5.2 An in-depth review of the economics of sea-level rise

With the aim of answering to Task 3.1a of Work Package 3, a specific review of the costs and benefits of adaptation to sea-level rise was carried out, additionally to the overall review presented previously. A total of 22 key studies were analysed, 14 of which included quantitative data that was collected in a comprehensive Excel spreadsheet (see Figure 2). The database includes 84 records (excel rows), each containing at least one data point but many of them including more than one. In general, infrastructural options (sea-wall defences) were more abundant than green or ecosystem based adaptation options.

Defining formal meta-analysis with the collected data was found to be very challenging, for the following reasons:

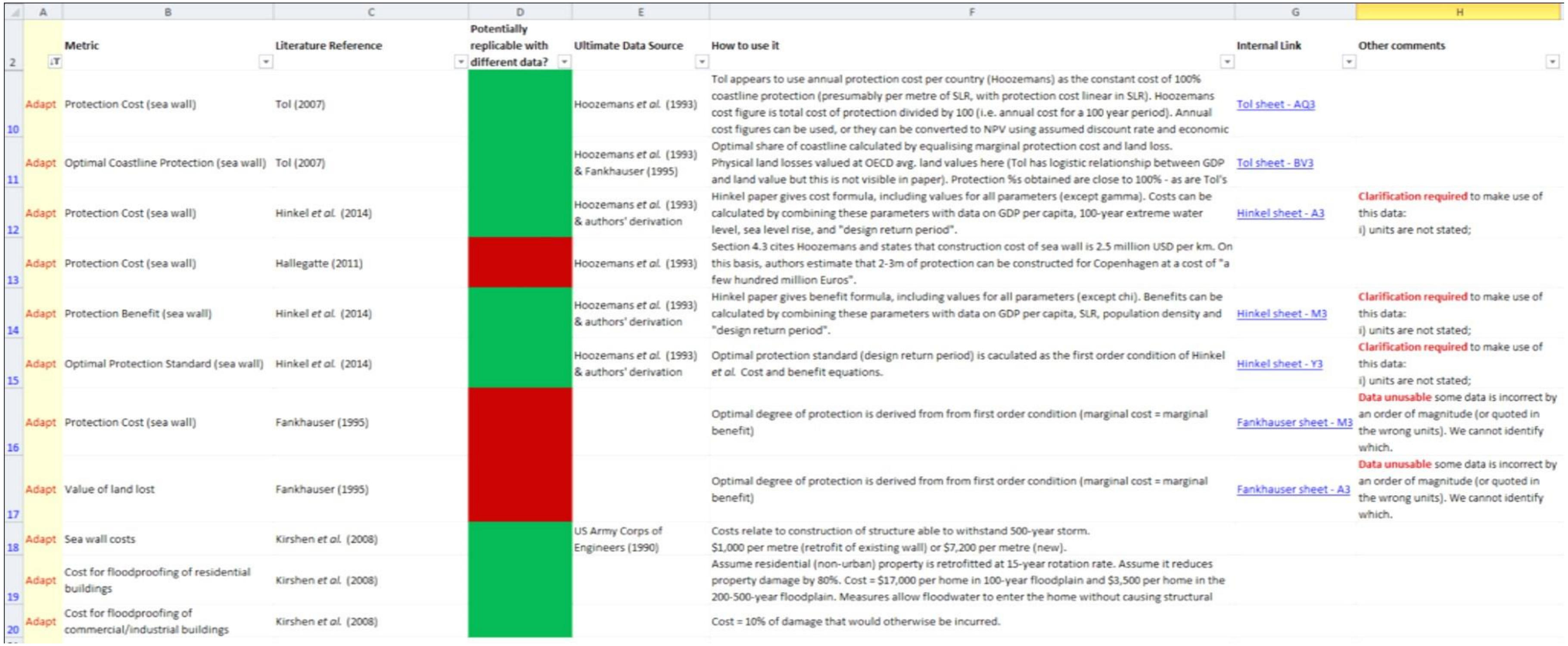
- Impacts are often specific to study and/or location;
- Data often come in ranges, where lower and upper bounds have a variety of meanings (different scenarios, different likelihoods etc.);
- Data are often totals rather than per unit values

In summary, the data lacked the necessary consistency to develop accurate benefit transfers. For this reason, a further in-depth review based on a selection of 6 key studies[3] was carried out in an attempt to define some guidelines for data transfer. Using this in-depth review we were mainly able to construct heuristics from the 2007 paper of Tol (2007), as well as collecting isolated pieces of information from other studies. Further information about this trial is provided in Section 7.2.

---

[3] Fankhauser, 1995; Tol, 2007; Hallegatte et al., 2011; Yohe et al., 2011; Hinkel et al., 2014; Neumann et al., 2014

Figure 2. Potentially usable data from studies reviewed, as captured in Excel file.



	A	B	C	D	E	F	G	H
2		**Metric**	**Literature Reference**	**Potentially replicable with different data?**	**Ultimate Data Source**	**How to use it**	**Internal Link**	**Other comments**
10	Adapt	Protection Cost (sea wall)	Tol (2007)	🟩	Hoozemans *et al.* (1993)	Tol appears to use annual protection cost per country (Hoozemans) as the constant cost of 100% coastline protection (presumably per metre of SLR, with protection cost linear in SLR). Hoozemans cost figure is total cost of protection divided by 100 (i.e. annual cost for a 100 year period). Annual cost figures can be used, or they can be converted to NPV using assumed discount rate and economic	Tol sheet - AQ3	
11	Adapt	Optimal Coastline Protection (sea wall)	Tol (2007)	🟩	Hoozemans *et al.* (1993) & Fankhauser (1995)	Optimal share of coastline calculated by equalising marginal protection cost and land loss. Physical land losses valued at OECD avg. land values here (Tol has logistic relationship between GDP and land value but this is not visible in paper). Protection %s obtained are close to 100% - as are Tol's	Tol sheet - BV3	
12	Adapt	Protection Cost (sea wall)	Hinkel *et al.* (2014)	🟩	Hoozemans *et al.* (1993) & authors' derivation	Hinkel paper gives cost formula, including values for all parameters (except gamma). Costs can be calculated by combining these parameters with data on GDP per capita, 100-year extreme water level, sea level rise, and "design return period".	Hinkel sheet - A3	**Clarification required** to make use of this data: i) units are not stated;
13	Adapt	Protection Cost (sea wall)	Hallegatte (2011)	🟥	Hoozemans *et al.* (1993)	Section 4.3 cites Hoozemans and states that construction cost of sea wall is 2.5 million USD per km. On this basis, authors estimate that 2-3m of protection can be constructed for Copenhagen at a cost of "a few hundred million Euros".		
14	Adapt	Protection Benefit (sea wall)	Hinkel *et al.* (2014)	🟩	Hoozemans *et al.* (1993) & authors' derivation	Hinkel paper gives benefit formula, including values for all parameters (except chi). Benefits can be calculated by combining these parameters with data on GDP per capita, SLR, population density and "design return period".	Hinkel sheet - M3	**Clarification required** to make use of this data: i) units are not stated;
15	Adapt	Optimal Protection Standard (sea wall)	Hinkel *et al.* (2014)	🟩	Hoozemans *et al.* (1993) & authors' derivation	Optimal protection standard (design return period) is caculated as the first order condition of Hinkel *et al.* Cost and benefit equations.	Hinkel sheet - Y3	**Clarification required** to make use of this data: i) units are not stated;
16	Adapt	Protection Cost (sea wall)	Fankhauser (1995)	🟥		Optimal degree of protection is derived from from first order condition (marginal cost = marginal benefit)	Fankhauser sheet - M3	**Data unusable** some data is incorrect by an order of magnitude (or quoted in the wrong units). We cannot identify which.
17	Adapt	Value of land lost	Fankhauser (1995)	🟥		Optimal degree of protection is derived from from first order condition (marginal cost = marginal benefit)	Fankhauser sheet - A3	**Data unusable** some data is incorrect by an order of magnitude (or quoted in the wrong units). We cannot identify which.
18	Adapt	Sea wall costs	Kirshen *et al.* (2008)	🟩	US Army Corps of Engineers (1990)	Costs relate to construction of structure able to withstand 500-year storm. $1,000 per metre (retrofit of existing wall) or $7,200 per metre (new).		
19	Adapt	Cost for floodproofing of residential buildings	Kirshen *et al.* (2008)	🟩		Assume residential (non-urban) property is retrofitted at 15-year rotation rate. Assume it reduces property damage by 80%. Cost = $17,000 per home in 100-year floodplain and $3,500 per home in the 200-500-year floodplain. Measures allow floodwater to enter the home without causing structural		
20	Adapt	Cost for floodproofing of commercial/industrial buildings	Kirshen *et al.* (2008)	🟩		Cost = 10% of damage that would otherwise be incurred.		

5.6 Water management

5.6.1 Revision process

Water management in this section refers to inland flood risk management, management of water demand, river basin management and integrated water resource management. Climate change is projected to modify global and regional hydrological cycles, raising the risk of more frequent and intense floods and physical threat to infrastructure, growing water supply deficits, and changing water quality (both drinking water quality and river dilution capacity). Changes in temperature averages may reduce snow recharge and speeding melting of glaciers, further intensifying low flows, supply deficits, and lower water quality. Water being a central natural resource for many sectors, adaptation to expected and unforeseen impacts on water resources is becoming a key priority in many countries. This section examines specifically costs and benefits of integrated water resource or river basin management, and more specifically of water sector adaptation (i.e. public water supply and wastewater services).

Table 5 presents the schema followed in the analysis of the literature. Impacts analysed include increased flood risks and reduced water availability and supply rates. Adaptation options include a range of technical (e.g. dyke construction), soft (e.g. awareness-raising), and green approaches (e.g. artificial wetland construction river restoration, land use change), and various water supply (e.g. additional abstraction and distribution, water storage, greywater re-use, transfers) and demand (e.g. leakage control, meters installation, water saving, water pricing) management options. The ECONADAPT literature database was searched for relevant studies on impacts and adaptation, resulting in the consideration of 70 relevant publications.

5.6.2 Main findings

Flood risk management

Climate change is projected to disrupt global and regional water cycles (IPCC, 2013). This leads to a number of potential risks, including more frequent and/or intense floods and changes to the water supply-demand balance, including potential water deficits (IPCC, 2014).

Projections of future climate change suggest extreme precipitation events will become more intense and more frequent by the end of this century in many areas (IPCC, 2013). This has the potential to increase river and surface water floods (flash floods) (Kundzewicz et al., 2014). There are a broad range of adaptation options to address these risks (Wilby and Keenan, 2012), many of which are similar to coastal flooding. However, the analysis of adaptation costs and benefits is more challenging in this area, because of the probabilistic nature of flooding extremes and the high site-specificity. Earlier reviews found a low coverage of cost-benefit assessments on this topic, but this has expanded significantly in recent years.

Table 5. Analysis of the literature: main impacts and adaptation measures.

Climate impact	Id	Adaptation measures	Description
Grey/technical measures			
Reduced availability and supply rate	1	Additional water storage and distribution	To retain water during high flow periods in order to provide additional resources during low flows and drought periods
	2	Additional abstraction and distribution	To abstract additional water from the aquatic environments and groundwater in order to meet water demand during whole year and low flows
	3	Rainwater harvesting	To capture rainwater usually for non-drinking purposes
	4	Greywater reuse and dual water systems	To collect wastewater, apply some form of purification, and re-use it for nondrinking purposes
	5	Leakage control	To reduce losses in the networks distributing drinking water and collecting wastewater
	6	Meters installation	To measure water use of individuals and businesses with the purpose to encourage lower water use
	7	Desalination	To pump seawater with the purpose of human consumption and economic use
	8	Water transfer	To collect water from one river basin with the aim of using it in another river basin
	9	Aquifer storage and recovery	To inject wastewater in ground waters with the purpose of using the water for human consumption and use
	10	Water shipment	To transport water (e.g. ice) from one world region to another, usually with the purpose of meeting water demand during a drought
	11	Water use efficiency	To encourage uptake of technologies capable of achieving the same function of previously used technologies with less water
Multiple risks	12	Improved/additional treatment	To improve/increase treatment of wastewater with the aim of reducing the environmental impact of wastewater release during low flows and droughts
Green infrastructure/nature-based solutions			
Multiple risks	13	Artificial wetlands	To construct wetlands that purify wastewater or rainwater, and thereby reducing the environmental impact of their release during low flows and droughts
	14	River restoration	To restore the water environment (e.g. re-meandering) with the objective of purifying wastewater or rainwater, and thereby reducing the environmental impact of their release during low flows and droughts
	15	Land use change	To change land use (e.g. re-naturation of industrial area, extensification of agriculture) with the objective of reducing the environmental impact of that land use
Soft measures			
Reduced availability and supply rate	16	Establishing market mechanisms	To establish prices and charges that encourage lower water use by individuals and businesses
	17	Cap and trade through water markets	To regulate the total use of water in a river basin while establishing a mechanism to exchange the right of using specified volumes of water
Multiple risks	18	Awareness-raising and education campaign	To increase knowledge and understanding of water scarcity and water pollution with the aim of changing the behaviour and environmental impact of individuals and businesses
	19	Improved forecasting	To invest into forecasting technologies and science with the aim of improving the knowledge of future changes in water availability and extremes
	20	Integrated management	To improve coordination and cooperation between water uses
	21	Change of water use	To re-locate households, businesses or industries to reduce water demand in a particular territory

At the global level, the World Bank's EACC study (2010) looked at the costs of flood protection, using a global hydrological model in an impact assessment. The study estimated the costs of adaptation at around USD 4-7 billion per year in the period 2010-50 for developing countries. At the regional, national and local scale, detailed hydrological models can be linked to probability-loss functions or depth damage functions to analyse adaptation costs and benefits. Such studies often assess the economic benefits of maintaining risk protection standards (e.g. maintaining a 1 in 100 year event under rising risks from climate change). These are then compared to the costs of flood protection, drawing on the costs of these programmes (e.g. Europe [HKV and RPA, 2014] and in the United States [MMC, 2005]). As an example, Rojas, Feyen and Watkiss (2013) estimated the economic benefits of adaptation from maintaining levels of river flood protection across Europe (EU27) (at a minimum 1 in 100 level) at EUR 8 billion per year by the 2020s, EUR 19 billion per year by the 2050s for a medium emission scenario (undiscounted). The authors concluded that these benefits were high compared to the likely costs of protection. There are similar studies at the national and river-basin level in many countries (e.g. in the Netherlands (Delta Committee, 2008; Bouwer et al., 2010) and the United Kingdom (Evans et al., 2004; Defra, 2011).

Such studies show that adaptation has potentially large benefits in reducing flood related damages under climate change. However, the scale of investment costs is also substantial, due to capital intensive flood defences and high maintenance costs. A similar finding emerges from investment and financial flow studies, which look at the likely increases in flood defence expenditure under climate change and find high additional costs (e.g. in Bangladesh [UNDP, 2011] and Nepal [IDS, 2014]) though also high benefits.

However, as with the coastal sector, many of these studies use impact assessment methodologies, and the same issues identified above therefore apply with respect to assumptions about foresight. As a consequence, adaptation is moving in a similar direction towards early low-regret options and consideration of uncertainty. There is some evidence on the costs and benefits of early low-regret options for flood protection in the existing disaster risk reduction 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 found an average benefit to cost ratio of just under 5 to 1 for flood related risks. This review was further expanded in ECONADAPT (2015) which found options with high benefit to cost ratios include:

- Meteorological and hydrological information, forecasting and use in early warning systems (e.g. in the United States [EASPE, 2002; MMC, 2005], in Europe [IDRS, 2008; Desbartes, 2012; World Bank, 2013], and for developing countries [World Bank, 2012]).
- Disaster risk management and emergency, contingency and preparation response plans and awareness raising (Hawley et al., 2012), as well as creating the enabling environment for adaptation (Wilby and Keenan, 2012).
- Enhanced maintenance regimes for drainage and sewage systems (e.g. Moench et al., 2009; ECA, 2009; Ranger et al., 2011).
- Risk transfer including insurance, reserve funds and risk pools and risk facilities, especially for more extreme events (see Jongman et al., 2014, for an analysis in Europe).

- Household level adaptation responses that can either reduce risks or reduce damage (as shown by adaptation cost curves in the United Kingdom (ASC, 2011) and analysis of household level options in developing countries (e.g. World Bank, 2011).
- Integrated water resource management (e.g. Mechler, 2005) and climate-smart agriculture (see later section).

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) – which are low-regret but not cost-free (Wilby and Keenan, 2012). There is evidence to suggest that the benefits of these options increase with greater levels of climate change (e.g. ECA, 2009), though on their own, there are limits (World Bank, 2011). There is also a greater focus – and evidence of higher benefit to cost ratios in developing countries – for community based interventions (see Moench et al., 2009). Mechler et al., 2014 highlights that there are a number of key assumptions and methodological challenges in such studies, and a key issue for the estimation of benefits is whether indirect and intangible effects are included.

As with coastal adaptation, there is also a move towards ecosystem-based and spatial options in a number of OECD countries. This includes spatial options that move beyond engineered control, such as the "room for the river" strategy in the Netherlands. These options include: watershed management including enhanced conservation and restoration, notably of upstream catchments; natural flood plain management, including water flow regulation and controlled flooding; and natural protection structures as an alternative to concrete. There has been a review of the costs and benefits of green schemes in Europe (HKV and RPA, 2014). This identifies studies on ecological variants (e.g. reed-land) of flood defences in the Netherlands (De Bel, Schomaker and van Herpen, 2011), wetland restoration in Stockholm (Kettunen, 2011), flood storage in the Humber estuary in the United Kingdom (EA, 2009c) and for the Elba in Germany (Teichmann and Berghöfer, 2010; TEEB DE, 2014). However, it is worth noting that benefits are often delivered in the future, due to the time for full ecosystem establishment (Naumann et al., 2011).

There has been less analysis of intra-urban flooding, though some country level studies consider adaptation costs (e.g. the United Kingdom [Evans et al., 2004] and Germany [Tröltzsch et al., 2012]). There are also examples at the city scale. Desjarlais (2011) performed a cost-effectiveness analysis of urban water drainage in Montreal. There are also cost-benefit studies of sustainable urban drainage systems (RH DHV, 2012). Most recently, Copenhagen has developed and undertaken a cost-benefit analysis for a cloudburst plan (City of Copenhagen, 2012). All of these studies show potentially high adaptation benefits, but investment costs are often very high.

There are also examples of iterative adaptive management (e.g. the Delta Programme Kind, 2014; Eijgenraam et al., 2014), real option analysis (for water and flood risk infrastructure in the United Kingdom (Gersonius et al., 2013) and robust decision making to flood risk management (e.g. in Ho Chi Minh City in Viet Nam: Lempert et al., 2013).

Water supply and management risks

Water supply and wastewater services – and the sectors and activities that rely on them – are vulnerable to climate change. However, there is high uncertainty, making adaptation challenging.

Adaptation to reduced water availability can include management of supply and demand. Supply measures include: increasing water storage capacity (e.g. the construction of dams or storage capacity, off-stream reservoirs, rainwater harvesting, artificial wetlands, off stream polders); improving water distribution (e.g. leakage control and meters); 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, behavioural change, and technological uptake (e.g. water efficient appliances). Early reviews (OECD, 2008) found few studies in this sector, but more evidence has emerged in recent years.

At the global level, the UNFCCC (2007) based on Kirshen (2007) was the first attempt estimating a required additional investment and financial flow of $9-11 billion per year in 2030 to deal with changes in the availability of water supply. The study focused on the costs of adaptation responses to water shortage using generalised cost functions applied to future supply-demand estimates at national level. The World Bank project “Economics of Adaptation to Climate Change” (World Bank, 2009; Hughes et al., 2010; Ward et al., 2010) also took an investment and financial flow analysis to estimate adaptation costs for developing countries from 2010 to 2050, including cost for municipal and industrial water supply (2005 prices, no discounting) of US$ 10 billion (wettest scenario) and US$11 (driest scenario). The study focused on the cost of providing enough raw water to restore future water demand using simple cost functions. Other aggregated estimates also exist. Hughes, Chinowsky and Strzepek (2010) estimated adaptation costs for water supply of 1–2% of baseline costs for all OECD countries, or about USD 5.5 billion per year.

There are also a number of studies at national level. An early national study of the costs of adaptation options was carried out for the Netherlands by Van Ierland and colleagues (Van Ierland, 2006; De Bruin et al., 2009). The study used a simple combination of qualitative, participatory-based multi-criteria analysis to prioritise adaptation options, followed by a CBA. It calculated incremental costs of climate proofing current policy based on 2006 Net Present Values using a discount rate of 4% (following Dutch government guidelines) for the period 2006-2050. Results suggest that climate-proofing the regional 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 areas €3.3 billion Euros, creating water storage on farmland €15 to 50 million, and upgrading sewer systems €3 to 5 billion. 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.

Tanaka et al. (2006) used a large-scale economic-engineering optimisation model of water supply called CALVIN to assess the long term performance of the Californian water management system under climate change. It is also used to illustrate how water management can adapt in an optimal way to climate change impacts in the context of higher future populations and changes in land use and technology. Measures considered include: 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. Results suggest that climate warming impact on water resources are of the same order to magnitude than changes in population-driven water demand, and that California can adapt to fairly severe growth and climate change, but that it may be costly.

There are also studies that use general equilibrium models to look at water adaptation costs, including Faust, Gonseth and Vielle (2012) in Switzerland, and analysis of network loss reductions by the Bank of Greece (2011). Metroeconomica (2006) estimated adaptation costs for anticipated water deficits in South-East England and South-East Scotland up to 2100, using indicative cost-curves and cost-effectiveness analysis. The annual cost of eliminating most water deficits for each region between 2006 and 2080 was 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 (2011b) developed household water adaptation cost curves for the United Kingdom. Studies also exist on water management at the local scale. Anderson (2008) examined the economic benefits of water reuse in Sydney in the context of future water supply and demand. Mánez and Cerdà (2014) used a cost-benefit analysis to prioritise adaptation measures in Valencia and Catalonia. Skourtos, Kontogianni and Tourkolias (2013) developed an adaptation cost database for technologies for water saving for use at the European level.

There are also studies in developing countries (see ECONADAPT [2015] for further information). These include a broad geographical coverage, with studies in Central America (Bárcena, A. et al., 2010), South Africa (Callaway et al., 2006), Kenya (SEI, 2009), Ethiopia (World Bank, 2010), Ecuador (Vergara et al., 2007), Nepal (Dhakal and Dixit, 2013), China (Kirshen et al., 2005), Costa Rica, Dominican Republic, the Gambia, Bangladesh, Honduras, and Peru (UNDP, 2011), Jordan and the Maldives (UNFCCC, 2010). 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 by trying to differentiate development and adaptation costs and benefits, and using 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 For example, the adaptation benefits of building new water storage capacity increased from ZAR 0.2 billion with current allocation rights to ZAR 5.8 – 7 billion with new allocation rights.

There are some estimates of the costs of adapting wastewater and storm-water infrastructure, as well as water treatment costs, under climate change. These include studies in the United Kingdom on the costs for upgrading wastewater networks due to more frequent low-flows in rivers (ICF International, 2007) and cost-effectiveness analysis for agriculture and sewage treatment works to comply with the EU Water Framework Directive and Habitats Directives in the context of climate change (mitigation and adaptation) at sub-catchment level (Martin-Ortega et al., 2012); in Toronto, Canada on the costs of building new treatment plants, improving the efficiency of plants or increasing retention tanks (Dore and Burton, 2001); and in Boston on the costs of extra treatment of wastewater under climate change (Kirshen et al., 2004). In particular, Martin-Ortega et al. (2012) applied a CEA approach to design adaptation and mitigation strategies for phosphorous reduction from agriculture and sewage treatment works to comply with the WFD and Habitats Directives, and test it for the Tame sub-catchment of the Thames catchment. The most cost effective combination of measures found was establishing ten metre 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. In Sweden, the costs of increased infrastructure were estimated for wastewater plans to address water supply contamination from climate change risks and increased separation/inactivation of micro-organisms in water treatment plants (SCCV, 2007). Sussman et al. (2014) collated national and regional estimates for adapting water infrastructure in the United States.

There are several studies on the costs of adaptation for hydro-electricity, 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 and Dubeux, 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 at European scale (Mima et al., 2011; CEPS/ZEW, 2010) and in some countries (e.g. in Germany [Tröltzsch et al., 2012]). Finally, there are some studies that consider adaptation costs for river transport, which is important on the major river systems of Europe. This includes analysis along the Rhine (Jonkeren, 2009) and other major river navigation routes (ECONET, 2014).

Recent discussion has moved towards low-regret adaptation options and the consideration of uncertainty. There are a set of early adaptation options that have high benefit to cost ratios (e.g. water efficiency measures, enhanced climate and hydrological monitoring and information [ECA, 2009; ASC, 2011]) as well as options that help improve watershed management (integrated water resource management and ecosystem based adaptation). There are also some examples of decision making under uncertainty, notably with robust decision making in California (Lempert and Groves, 2010), the Colorado River Basin (Groves et al., 2013) and for dam design in Greece (Nassopoulos et al., 2013), an application of real options analysis (Jeuland and Whittington, 2013) to water investment planning on the Blue Nile for large dams, and an application of decision pathways (iterative risk management) for water investment planning in London (Darch et al., 2011). For example, Lempert and Groves (2010) assessed the performance of the current management plan of a water and wastewater utility in Southern California under 450 potential futures. The study found that the current plan is likely to result in high costs (above $3.75 billion) for 116 potential futures (out of 450), while including an adaptive approach reduces these cases to 33. Including in addition adaptation measures future reduces significantly potential high cost outcomes (down to 1), but may come at a high transaction cost.

5.7 Biodiversity and ecosystem services

5.7.1 Revision process

An initial structured review of the literature was defined, following the search criteria shown in Table 6. Key individual terms (and Wildcard symbols (*) where appropriate) separated by Boolean “OR” operators and sets combined using “AND” were introduced in the Web of Knowledge database. The timeframe considered was 2006-2015 and only Europe, the US and Canada were considered in the geographical areas. The search provided more than 150 studies, but a quick screening showed that most of them were missing cost and benefit estimates, and an adaptive approach was often not found.

The search strategy needed to be changed: several studies addressing ecosystem-based adaptation (EbA) were reviewed next, which rarely provided any costs and benefits, but that allowed us to define a structure for the review. In this way, two main search-groups were identified: EbA and early low-regret options for adaptation. In the first group we specifically looked for data on ecosystem restoration, conservation, maintenance (or improvement) and green-infrastructure. Within early-low regret options we focused on reinforcement or enlargement of existing measures to protect biodiversity (e.g. use of protected areas, buffer zones, ecological corridors, reducing habitat fragmentation) and other new approaches (e.g. selection of species, translocation of species, management of alien species).

Table 6. Initial search criteria defined for the literature review.

Adaptation	adaptation OR adaptive OR vulnerable OR vulnerability OR coping OR resilience OR resilient OR adapt OR cope OR "disaster risk reduction"
	AND
Climate change	"climate change" OR "climate variability" OR "climate hazard" OR "extreme weather" OR "natural hazard" OR disaster OR flood OR drought OR hurricane OR storm OR cyclone OR "sea level rise" OR "irregular rainfall" OR "intense rainfall"
	AND
ecosystem	ecosystem OR wetland OR forest OR woodland OR dryland OR grassland OR "coral reef" OR biodiversity OR coastal OR mangrove OR tree OR agro forestry OR biodiversity
	AND
	cost* or benefit*
	AND
EbA	"ecosystem-based adaptation" OR "ecosystem services" OR "green infrastructure" OR "ecological infrastructure" OR "soft infrastructure" OR "natural infrastructure"

The current database includes 25 studies and 64 observations, even though many more references were checked that did not provide with cost or benefit estimates.

5.7.2 Main findings

Climate change poses potentially large 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 species extinction (Settele et al., 2014). Previous reviews have identified a major gap in this area, reflecting the challenges involved in quantification and valuation. The literature that does exist focuses on the costs of protection and restoration of habitats and species, though there is literature on ecosystem based adaptation (“green” options) discussed in earlier sections.

Even if ecosystem based adaptation (EbA) is primarily intended to reduce the vulnerability of people, it remains true that it is possible to contribute to human well-being while increasing and improving ecosystem resilience (Fedele et al., 2015). Considering that in many places of the world, natural resources represent the base of local economies, the EbA approach results especially interesting for many of the most vulnerable areas and it has clear synergies with community-based adaptation processes and local livelihoods and knowledge. Also, it is usually more cost-effective than traditional grey engineering solutions. In Viet Nam, planting mangroves as a way to increase coastal resilience to typhoons had a cost of US$1.1 million, while saving US$7.3 million on levee maintenance costs (Reid and Huq, 2005). This measure provided additional co-benefits by improving livelihoods based on shellfish harvesting. In fact, it is frequent that EbA measures imply further benefits beyond climate adaptation. In contrast, the effects of hard measures are generally limited to the function for which they were implemented (Jones et al., 2012). See, for example, Tri et al. (1998) and Emerton et al. (2009).

Nevertheless, EbA approaches are not exclusive of developing countries. They can be a key cost-effective alternative in developed countries as well (Ojea, 2015). For example, Doswald and Osti (2011) offer a good review of projects already implemented in Europe, although no information is provided in relation to the economic costs and benefits of the analysed projects. Based on a literature review, Jones et al. (2012) construct three examples of EbA approaches and compare their costs and benefits against hard or engineering measures. The examples deal with disaster risk protection in coastal areas, sustainable water management and food security and are located both in developed and developing countries.

Another relevant issue that deserves attention regarding EbA approaches is that they provide flexibility, as many ecosystems have the capacity to adapt to certain levels of change. That is the case, for example, of salt marshes that accrete as a response to sea-level rise when some conditions are met. This represents a strong advantage in a context of great uncertainty. While a hard infrastructure may be obsolete in the future if either the expected climatic or socioeconomic conditions change, EbA can be useful for avoiding maladaptation (Jones et al. 2012).

In relation to global costs, earlier studies (Berry, 2007) estimated the overall costs of establishing and managing protected areas under climate change at USD 36-65 billion per year by 2030, noting the costs would be as high as USD 290 billion per year when extended to conservation of the wider matrix of landscapes. Some studies at national level also exist. Berry et al. (2006) estimated the adaptation costs (for restoration and re-creation) in the United Kingdom for a number of habitats. The UNDP investment and financial flow analysis of Costa Rica estimated the costs of adaptation for the biodiversity sector (i.e. conservation of terrestrial, marine and aquatic ecosystems, prevention of forest fires, and awareness raising) at USD 60 million per year in 2015 rising to USD 76 million per year in 2030, i.e. a total of USD 1.3 billion over the period (UNDP, 2011). A similar study in Peru (UNDP, 2011) estimated adaptation costs for fisheries at USD 0.78 billion to 2030 (i.e. approximately USD 40 million per year). Van Ierland et al. (2006) estimated the costs of establishing a national ecologic network, in the Netherlands and additional adaptation under climate change at EUR 135 million per year.

Cartwright (2013) analyses adaptation measures in a metropolitan region in Durban, South Africa, finding positive benefit-cost ratios for the three ecosystem-related measures. While most early low-regret options 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), there are some new approaches (e.g. selection of species, translocation of species, management of alien species), alongside enhanced information and monitoring. 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.

However, there is very little evidence on the costs and benefits of these options: one study in Finland analysed the conservation of grassland butterflies under a changing climate (Tainio et al., 2014) finding that buffer zones were most cost-effective while the costs of translocation were relatively modest compared to dispersal corridors.

Nonetheless, in recent years, more literature on the value of ecosystem services has emerged (TEEB, 2009; TEEB 2010) that provides potential inputs for the analysis of adaptation costs and benefits. These studies highlight the economic values of restoration projects as an adaptation measure, and have assessed the benefit to cost ratio for restoration of different biomes and ecosystem, finding high benefit to cost ratios, especially for grassland, tropical forests, wood- and shrub-land, and mangroves.

There is also an increased interest in the application of adaptive management to this sector, though studies to date have not focused on economics. 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).

A key conclusion is that the evidence base remains limited, and the information that does exist is difficult to transfer, due to the complexity of estimating the impacts of climate change, and the additional challenge of valuation. The studies that do exist indicate that aggregate costs could be high, and that there are potential opportunity and policy costs. This sector remains a priority for research.

6 The costs and benefits of adaptation: using meta-analysis for benefit transfer

Where no previous economic information is available on the value of an environmental good or service, there are several methods that could be used to measure it in monetary terms. These methods can be classified into three main categories, although this classification varies depending on the authors (see, for example, de Groot et al., 2002; Liu et al., 2010; TEEB, 2010). The first group includes market based approaches that reflect the real preferences or costs (or benefits) to individuals. The second group consists of revealed preference approaches that are based on the observation of individual choices through which people show their preferences in relation to the good or service under valuation. Finally, the stated preference approach is used to simulate a market by using surveys on hypothetical changes in the provision of goods or services caused by policy changes.

However, resources or time constraints may limit or prevent new primary valuation studies from being undertaken; instead, a benefit transfer (BT) method could be used. A benefit transfer consists of taking an estimate from previous research (i.e. the value provided by salt marsh ecosystems in a certain location) and transferring it to value an analogous ecosystem (Smith et al., 2002). The site from which values are taken is known as "study-site" and the place where values are being transferred to is called "policy-site" (Galarraga et al., 2004).

There are three ways in which a benefit transfer can be developed:

- The more basic approach, called unit BT, consists of the assumption that the single value of an ES in the study-site is approximately equal to that in the policy-site. This value is thus directly transferred, making some adjustments when necessary (currency, income…).

- In the value function transfer, the whole benefit (or damage) function is transferred, not only the value obtained at the study-site. From a conceptual point of view this is a more rigorous procedure as more information is used for the value transfer. In this way the valuation function used as the study-site is applied at the policy-site by introducing information and parameters from the area under study.

- Finally, the meta-analytic function transfer can be used. The difference with the previous approach relies on the fact that this function is built based on multiple values from different studies. That is, the value for the study-site estimated with this approach is not obtained from one single study but from a compilation of values obtained from a meta-analysis (Galarraga et al., 2004; TEEB, 2010).

Regarding the definition of Task3.1 (a), the focus of this section is on meta-analysis (MA), which can be defined as "the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings" (Glass, 1976: 3). The meta-analysis has been long used in different disciplines, such as medicine, education, psychology or social sciences. In environmental economics the most common technique is meta-regression analysis (Nelson and Kennedy, 2009), that typically incorporates a wide range of socio-economic and physical attributes of the study-sites, including different valuation methods, that cannot be taken into account when undertaking value function transfers based on a single or a few primary valuation studies (TEEB, 2010). Thus, many authors advocate that MA transfer functions represent a more robust approach to benefit transfer than using alternative transfer methods (see, for example, Moeltner et al., 2007; Stapler and Johnston, 2008; Johnston and Rosenberger, 2009; Brander et al., 2012). Despite MA outperforming unit and value function transfers, Rosenberg and Stanley (2006: 377) remind us that the final quality of benefit transfers depends on the data on which they are built. Furthermore, Nelson and Kennedy (2009: 370) state that "it is easy to do a meta-analysis, but it is difficult to do a good one".

6.1 Challenges and limitations of meta-analysis

The review of the use of MA in environmental economics has identified several challenges of this widespread method. Next we describe the main issues that can compromise the reliability of benefit transfers that have also been found to be relevant in the literature reviews carried out within WP3 – Task 1.

The first issue is related *primary data heterogeneity* (Nelson and Kennedy, 2009), also called *commodity consistency* (Bergstrom and Taylor, 2006). Heterogeneity is *factual* when the commodity under assessment differs across primary studies. For example, the benefits provided by wetlands in some studies can be measured in terms of flood protection, while in others they might depend on carbon sequestration or provision services related to fishing. Commodity consistency, or the lack of it, can also refer to different ranges or scales across different studies.

Heterogeneity can also be methodological, when it is related to the use of different methodologies or study design in the reference primary studies. For example, Bergstrom and Taylor (2006) argue that contingency valuation methods (CVM) and travel cost methods (TCM) measure different consumer surplus: the first uses the Hicksian welfare change measure, while the second uses the Marshallian surplus.

The literature offers some solutions to commodity inconsistency, such as calibration, adjusting the dependant variable, including new explanatory variables or dividing the sample into smaller and more homogeneous sub-samples. The latter is limited by the size of the sample and it will not always be possible to define smaller groups. Calibration will not always be feasible as it requires sufficient information from the primary studies that is not commonly available. Adjusting the dependant variable could turn out to be problematic if it essentially changes what has been measured or valued in the primary studies. Adding new explanatory variables, typically dummy variables that theoretically can capture the effect of the study design or the different valuation methods, is a quite common solution. However, it is not out of question as it may imply the introduction of “linearity assumptions or restrictions to the model” (Bergstrom and Taylor, 2006: 354). Additionally, Nelson and Kennedy (2009: 368) point out that effect-sizes estimated in a MA that is based on primary study regressions that do not consider the same explanatory variables “are likely biased to different degrees”.

In fact, this potential solution to heterogeneity may not always be appropriate. When trying to transfer landscape values obtained in primary studies using discrete choice experiments (DCE), De Ayala et al. (2014) found that the sample showed an important heterogeneity: different types of landscapes were assessed through the definition of various kinds of attributes, which were also defined in several ways. As a result, they concluded that it was extremely difficult to guarantee commensurability across the different primary studies, unless a high number of subjective assumptions were made.

This is a recurrent issue in the reviews carried out within WP3: there is a general lack of uniformity in the data on costs and benefits of adaptation options that makes it extremely difficult to perform a benefit transfer. For example, in relation to heat warning systems, the main issue is related to the health impact assessment and the choice of a common unit to measure the threshold temperature. In the case of ecosystem services the common unit is not generally a problem, as either costs or benefits are most often provided in monetary units per hectare. However, other heterogeneities have been found, those related to commodity consistency (different studies measuring different services within the same group or ecosystem) but also methodological heterogeneity linked to differences in the design or method used in the primary study (e.g. CVM, TCM, etc.)

The second issue to be accounted for when performing a MA refers to *correlation*, meaning the interdependency of multiple records that are based on the same primary study. The most common reasons for this interdependency can be found in the use of the same data sources (i.e. same public database) but especially for inferring more than one estimate from each primary study (Nelson and Kennedy, 2009). Although the simplest way to avoid correlation is using a single estimate per primary study, this can lead to an extremely small sample and so it will often not be an alternative. Some other adjustments could (and should) be used for adjusting for dependency (e.g. econometric methods). In their review of MA studies, Nelson and Kennedy (2009) found that 79% of the MA studies used more than one estimate from each original and 34% of them did not account for correlation at all.

The literature on costs and benefits of adaptation is relatively new and therefore, not overly extensive as yet, even though it varies greatly across and within sectors. The experience of Task 3.1a shows that in order to define a big enough sample all the available data points need to be collected, even if they have been estimated in the same studies. Correlation is something that will need to be dealt with, if it has been possible to perform the MA at all.

The third issue that needs to be considered is the *generalization error* that according to Rosenberger and Stanley (2006) represents one of the main sources of error in benefit transfers. This generalization error is intrinsic to the benefit transfer itself as it relates to the adaptation of the estimates from study sites to policy sites. Thus, the greater the correspondence between study and policy sites, the lower the errors. As previously said, the MA transfer functions perform benefit transfer methods more accurately than others, due to the option of incorporating variables describing the specific features of the policy sites. However, the improved performance seems to be more related to the similarity between sites than to the function itself.

This third methodological issue is also relevant for the work done within Task 3.1a. The review has focused on European studies, but there is a great variability across locations in terms of scale (global, regional, local), cultural differences, intensity of impacts (e.g. some impacts will affect harder Southern countries) and socio-economic features. Furthermore, several studies explicitly mention results as being context specific (Rickson et al., 2010; Riksen et al., 2003; Sutton et al., 2013; Tim Chamen et al., 2015). By extension, this raises the question about the appropriateness of the use and transferability of such data to different policy sites.

Nevertheless, a trial has been made in an attempt to obtain some rules of thumb that could be useful in the context of adaptation to sea-level rise. Further details are described in the next section.

6.2 Sea-level rise: heuristics based on the literature[4]

As previously explained in Section 5.5.2, six key studies have been reviewed in-depth to test the feasibility of using this approach for deriving "rules of thumb" (heuristics) that can be applied to other sites (see Section 0). For this purpose, we created an Excel file which catalogues the data that is potentially usable from each study and performs a number of calculations as the study's instructions dictate. The front page of this Excel file is shown in Figure 2.

We were able to replicate the methods of Tol (2007) and Hinkel et al. (2014) (although we were not able to verify if we had successfully replicated their results since the results themselves are not given to the required degree of detail). We also extracted some simpler heuristics from Kirshen et al. (2008) (sea wall costs per metre, cost of flood proofing for residential, commercial and industrial buildings).

---

[4] This section presents part of the work carried out in relation to the economics of sea-level rise. The full report is included in Appendix 1.

In the case of Tol (2007), we were able to calculate protection cost (USD) and optimal shoreline protection (%), assuming for simplicity that OECD average coastline values apply to all countries. This gave values of optimal protection area (for 1 metre SLR) ranging from 100% of coastline to 0% for sparsely populated countries with lots of coastline (including Denmark). Using different coastline values (e.g. scaling by GDP/capita) would undoubtedly produce different results.

In the case of Hinkel et al. (2014), it was possible to replicate the paper's formulae for the costs and benefits of protection and obtain a plausible optimal return period, subject to minor clarifications regarding the units of some of the parameters. For example it was estimated that a sea wall should have an optimal design return period of 850 years (i.e. it should be able to withstand an event of 1/850 year magnitude) when the following (hypothetical) input data is assumed:

- a 5 metre inundation event occurs at 1/100 year frequency;
- 2.5 metre permanent SLR is expected
- 'scaled' GDP per capita is $35,0008
- Population density of 70 people per km2

In the case of Fankhauser (1995) we were unable to replicate the optimal protection calculations. Our calculations produced protection costs that were greater than benefits by one order of magnitude, whereas the original paper found that the majority of coastline should be protected in most cases. We were unable to clarify possible reasons for this with the author.

The main conclusions of this exercise can be summarised as follows:

- Quality and detail of data has improved: comparison of recent studies against the older analysis of Fankhauser (1995) and Tol (2007) shows that considerable progress has been made in quantifying economic exposure to SLR. Per-country estimates have been replaced with detailed models & databases of coastal topography, and the distribution of people and assets.
- All papers show limitations: notable limitations acknowledged in each paper include the need to consider the effect of climate change on storminess, and the need to consider a wider range of adaptation options than the hypothetical sea wall (and flood proofing) considered in most cases. Some authors also note that the comparison between 'with adaptation' and 'no adaptation' cases is merely illustrative and is unrealistic as a 'true' damage estimate (since autonomous adaptation, or even maladaptation is likely to occur once emerging SLR risks become apparent). Furthermore, some calculations are based on heuristics with limited empirical support. E.g. Hinkel et al. (2014) uses a single asset:GDP ratio to convert spatial population data into estimates of exposed assets
- The state of the art appears to be more advanced in impacts than adaptation: In terms of costing the adaptation options identified, three studies rely on cost data from Hoozemans et al. (1993). With the exception of Neumann, all studies use cost data from 2000 or earlier, while some do not adjust wall height to take account of different SLR scenarios, or assume that wall costs are linear in SLR. The validity of these assumptions appears to be largely untested and may therefore be an important area for investigation.
- The methods to estimate the losses are heterogeneous: in many studies, the losses from SLR consist of repair costs and the value of assets abandoned, but Fankhauser (1995) instead considers losses to be the lost income stream from land that is permanently inundated. Hallegatte et al. 2011

also considers indirect losses, which though small (under 10% of total loss over the range considered) increase rapidly as sea level rises. Yohe et al. (2011) also considers the effect of risk preferences, arguing that the value of a possible loss is greater than the 'certainty equivalent' value of the damage, once agents' likely risk aversion is taken into account.

- 'Marginal' decision makers need better information in neglected areas: this review has shown that in many cases, the benefits of adaptation exceed the cost by several orders of magnitude. However when investment decisions are marginal, neglected factor become more important (such as the state of the insurance market and the quality of protection cost data). This is particularly true when adaptation funds are scarce or the optimal timing of the investment is debatable. Therefore, it is reasonable that scientific improvements up to now have concentrated on the largest cost item (exposure), particularly when analysing SLR over the long-term and at low spatial resolution. However if the goal of future analysis is to move to a more 'marginal' intervention space (i.e. closer in time and higher geographical resolution), greater attention should be paid to adaptation costs and the role of risk and insurance.

7 Discussion of the current state of evidence and key gaps

An analysis of the evidence above reveals a number of key insights in relation to the costs and benefits of adaptation. Most of these estimates are from grey literature – only 25% are academic peer-reviewed articles (ECONADAPT, 2015). Moreover, most of the evidence is based on classic scenario-based impact assessment methods. This means that the majority of the studies are theoretical, focus on technical adaptation, and ignore uncertainty. Earlier studies show that adaptation has very high benefit to cost ratios and potentially low costs, though more recent studies indicate they are probably over-optimistic. As the evidence base in this area is still emerging, there is an urgent need for more empirical studies to address key gaps and to ensure information and lessons can be shared.

Perhaps most interestingly, there has been a major shift in the evidence base over the past few years and this provides a number of key insights. First, more recent studies focus on early adaptation and low-regret options. That is, they identify different early options (with more focus on adaptive capacity, the valuation of information and soft options). Many of these early low-regret options will have lower costs than engineering based options (Agrawala et al., 2011a), and they often offer wider co-benefits. However, they are only the initial steps in a longer adaptation pathway, and are introduced early in the planning process, at a time when classic impact assessment studies induce very little action.

Second, more recent studies are more grounded in existing sectoral policy. Such studies identify that many adaptation options will have important opportunity, transaction or policy costs (DFID, 2014), which are not included in the earlier technical studies. These costs arise even for low-regret options such as climate-smart agriculture or ecosystem-based adaptation. Experience from the mitigation domain has demonstrated that it is rarely as easy or cheap to implement low or no regret options as expected, due to a range of economic, information and policy barriers. There is also an increasing recognition that implementation costs in developing countries will need to consider existing development and governance challenges, which are likely to affect the effectiveness of adaptation or the costs of delivering options.

Third, more recent studies frame medium and longer-term adaptation in a different way, using iterative risk management or decision making under uncertainty. The methods themselves are therefore different to the older studies, and they identify different options as a result. These approaches provide high potential benefits, using adaptive management to avoid future inefficient or ineffective adaptation. However, these approaches require higher adaptive capacity to implement than earlier studies.

Finally, doing an accurate and reliable MA in order to be used for benefit transfer within a sector across Europe has proven to be extremely difficult. Heterogeneity, both factual and methodological, is the major limitation as there is a general lack of consistency in the collected data, but it adds up to other problems such as correlation or generalisation error. Nevertheless, a trial exercise has been performed in relation to the economics of sea-level rise. Using the in-depth review method it has been possible to construct heuristics from the results of Tol (2007), as well as collecting isolated pieces of information from other studies. For example, Hallegatte et al. (2011) and Kirshen et al. (2008) cite other studies in claiming that the costs of a sea wall are around $2.5 million and $1-7.2 million respectively. The most interesting heuristic resulting from this exercise is the optimal protection period calculation derived from Hinkel et al. (2014). However, this is only a formula (for which some parameters had to be estimated). Additional data and quality control would therefore be required in order to deploy this formula in further analyses.

References

Aaheim, A., Amundsen, H., Dokken, T. and Wei, T. (2012). *Impacts and adaptation to climate change in European economies*. Global Environmental Change, Volume 22, Issue 4, October 2012, Pages 959968.

Ackerman, F. and E.A. Stanton (2008), *The Cost of Climate Change: What We'll Pay if Global Warming Continues Unchecked*, The Natural Resources Defense Counsil, New York.

Acosta, R. and Skea, J. 1995. Industry, Energy, and Transportation: Impacts and Adaptation. IPCC working Group II.

Adams, S., Hamilton, R., Vynne, S., and Doppelt, B. (2010). Additional analysis of the potential economic costs to the State of Washington of a business as usual approach to climate change: lost snowpack water storage and bark beetle impacts, The Program on Climate Change

Adamson, D., T. Mallawaarachchi and J. Quiggin (2009), *Declining inflows and more frequent droughts in the Murray-Darling Basin: Climate change, impacts and adaptation*, Australian Journal of Agricultural and Resource Economics, Vol. 53(1), *http://dx.doi.org/10.1111/j.14678489.2009.00451.x*.

ADB (2005), *Climate Proofing: A Risk-based Approach to Adaptation*, Asian Development Bank, Manila.

ADB (2009), *The Economics of Climate Change in Southeast Asia: A Regional Review*, Asian Development Bank, Manila.

ADB (2014), *The Economics of Climate Change in South Asia*, Asian Development Bank, Manila.

Adger, W.N. et al. (2007), *Assessment of adaptation practices, options, constraints and capacity*. *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 717743.

Aebischer, B., Jakob, M. and Catenazzi, G. (2007). Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. ECEEE 2007 SUMMER STUDY SAVING ENERGY – JUST DO IT!" Aerts, J.C. et al. (2013), *Cost estimates for flood resilience and protection strategies in New York City*, Annals of the New York Academy Sciences, Vol. 1294, *http://dx.doi.org/10.1111/nyas.12200*.

Aerts, J.C. et al. (2014), *Evaluating Flood Resilience Strategies for Coastal Megacities*, Science, Vol. 344(6183), *http://dx.doi.org/10.1126/science.1248222*.

AfDB (2011), *The Cost of Adaptation to Climate Change in Africa*, African Development Bank, Tunis.

Agrawala, S. and Fankhauser, S. 2008. Economic Aspects of Adaptation to Climate Change. Costs, Benefits and Policy Instruments. OECD.

Agrawala, S. et al. (2011a), *Adapting to Climate Change: Costs, Benefits, and Modelling Approaches*, International Review of Environmental and Resource Economics, Volume 5(3), *http://dx.doi.org/ 10.1787/5km975m3d5hb-en*.

Agrawala, S. et al. (2011b), *Plan or React? Analysis of adaptation costs and benefits using integrated assessment models*, Climate Change Economics, Vol. 2(3), *http://dx.doi.org/10.1142/S2010007811000267*.

AIACC (Assessments of Impacts and Adaptations to Climate Change) (2006), *Estimating and Comparing Costs and Benefits of Adaptation Projects: Case Studies in South Africa and The Gambia*, report submitted to Assessments of Impacts and Adaptations to Climate Change, the International START Secretariat, Washington, DC.

Aivalioti, S. (2015). Electricity sector: adaptation to heat heaves. Columbia Law School

Akpinar-Ferrand, E. and A. Singh (2010), *Modeling increased demand of energy for air conditioners and consequent CO2 emissions to minimize health risks due to climate change in India*, Environmental Science and Policy, Volume 13(8), *http://dx.doi.org/10.1016/j.envsci.2010.09.009*.

Alberini A. and Chiabai, A. (2007). *Urban Environmental Health and Sensitive Populations: How Much are the Italians Willing to Pay to Reduce their Risks?* Regional Science and Urban Economics, Vol. 37: 239–258.

Alka Sapkota, Zhibo Lu, Haizhen Yang, Juan Wang (2014). Role of renewable energy technologies in rural communities' adaptation to climate change in Nepal. Renewable Energy 68 (2014) 793-800

Altvater, S. et al, (2012). Adaptation Measures in the EU: Policies, Costs, and Economic Assessment "Climate Proofing" of key EU policies. Ecologic.

Altvater, S. et al. (2012): Adaptation Measures in the EU: Policies, Costs, and Economic Assessment."

Amelung, B. and Moreno, A. (2012), *Costing the impact of climate change on tourism in Europe: results of the PESETA project*, Climatic Change *http://dx.doi.org/10.1007/s10584-011-0341-0*.

Anderson, J.M. (2008), *Adapting to climate change with water savings and water reuse*, Water Practice & Technology, Volume 3(2), *http://dx.doi.org/10.2166/WPT.2008036*.

Arent, D.J. et al. (2014), Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Arup (2008), *Your home in a changing climate: Retrofitting existing homes for climate change impacts*, Report for the Three Regions Climate Change Group, Greater London Authority, London.

ASC (Adaptation Sub Committee) (2011), *Research to identify potential low-regrets adaptation options to climate change in the residential buildings sector*, a report prepared by Davis Langdon for the Adaptation Sub Committee.

ASC (Adaptation Sub Committee) (2014), *Managing climate risks to well-being and the economy*, Adaptation Sub Committee Progress report *2014*.

Asian Development Bank (2012). Climate Risk and Adaptation in the Electric Power Sector. "

Atkins (2013), *Economics of climate change adaptation and risks*, a report prepared for the Highways Agency.

Bafu 2011: URL www.bafu.admin.ch/naturgefahren/01920/index.html?lang=de

Bank of Greece (2011), *The environmental, economic, and social impacts of climate change in Greece*, Climate Change Impacts Study Committee, Athens.

Bárcena, A. et al. (2010), *The Economics of Climate Change in Central America*, ECLAC Subregional Headquarters in Mexico, Mexico City and Centeral American Integration System (SICA), El Salvador.

Bates, B.C., et al. (2008). Climate change and water. Intergovernmental Panel on Climate Change.

Beecher, J. and Kalmbach, J. (2012), *Climate Change and Energy*, U.S. Global Change Research Program National Climate Assessment Midwest Technical Input Report.

Bergstrom, J.C., Taylor, L.O., 2006. Using meta-analysis for benefits transfer: Theory and practice. Ecol. Econ. 60, 351–360. doi:10.1016/j.ecolecon.2006.06.015

Berry, P. (2007), *Adaptation options on natural ecosystems*, a report for the UNFCCC Secretariat, Financial and Technical Support Division.

Berry, P., Hunt, A. and Nunes, P. (2006), Chapter 6: Biodiversity in *Task 3 Report – Climate change impacts and adaptation: Cross-regional research programme, Project E – Quantify the cost of future impacts*, report by Metroeconomica Ltd. for Defra.

BIS (2013), *Adaptation and resilience (climate change)* (A&RCC), Published by Department for Business, Innovation & Skills, Department for Environment, Food & Rural Affairs and Department of Energy & Climate Change.

Bölscher, T. et al. (2013), *Adaptation Turning Points in River Restoration? The Rhine Salmon Case*, Sustainability, Volume 5(6), *http://dx.doi.org/10.3390/su5062288*.

Bosello F. et al. (2012), *Economic impacts of climate change in Europe: sea-level rise*, Climatic Change, Vol. 112(1), *http://dx.doi.org/10.1007/s10584-011-0340-1*.

Bosello, F., C. Carraro and E. De Cian (2009), *An Analysis of Adaptation as a Response to Climate Change*, Working Paper, No. 26, Department of Economics Ca' Fosari University of Venice.

Bosello, F., C. Carraro and E. De Cian (2013), *Adaptation Can Help Mitigation: An Integrated Approach to Post 2012 Climate Policy*, Environment and Development Economics, Vol. 18(3). *http://dx.doi.org/10.1017/ S1355770X13000132*.

Boselly, S. E. (2001), Benefit/Cost Study of RWIS and Anti-icing Technologies.

Boughlala, M., 2013. Better economics: supporting climate change adaptation with stakeholder analysis: a case study of Morocco. International Institute for Environment and Development (IIED).

Boughlala, M., 2013. Better economics: supporting climate change adaptation with stakeholder analysis: a case study of Morocco. International Institute for Environment and Development (IIED).

Bouwer, L.M., P. Bubeck and J.C.J.H. Aerts (2010), *Changes in future flood risk due to climate and development in a Dutch polder area*, Global Environmental Change, Volume 20(3), *http://dx.doi.org/10.1016/ j.gloenvcha.2010.04.002*.

Boyd, R. and A. Hunt (2004), *Costing the impacts of climate change in the UK: Overview of guidelines*, UKCIP Technical Report, UKCIP, Oxford, July 2004

Branca, G. et al. (2011), *Climate-Smart Agriculture: A Synthesis of Empirical Evidence of Food Security and Mitigation Benefits from Improved Cropland Management*, Mitigation Of Climate Change In Agriculture Series, No. 3, FAO, Rome.

Branca, G., L. Lipper and A. Sorrentino (2012), *Benefit-costs analysis of climate-related agricultural investments in Africa: A case study*, Italian Association of Agricultural and Applied Economics, Congress Papers, 2012 First Congress, June 4-5, 2012, Trento, Italy.

Branca, G., McCarthy, N., Lipper, L., Jolejole, M.C., 2011. Climate Smart Agriculture: A Synthesis of Empirical Evidence of Food Security and Mitigation Benefits from Improved Cropland Management.

Brander, L.M., Bräuer, I., Gerdes, H., Ghermandi, A., Kuik, O., Markandya, A., Navrud, S., Nunes, P.A.L.D., Schaafsma, M., Vos, H., 2012. Using meta-analysis and GIS for value transfer and scaling up: Valuing climate change induced losses of European wetlands. Environ. Resour. Econ. 52, 1–19.

British Columbia (2013), *Farm Practices & Adaptation*, Climate Action Initiative, *www.bcagclimateaction.ca/ adapt/farm-practices/*.

Broekx, S. et al. (2011), *Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach*, Natural Hazards, Volume 57(2), *http://dx.doi.org/10.1007/s11069-010-9610x*.

Brown S. et al. (2011), *Sea-Level Rise: The Impacts and Economic Costs of Sea-Level Rise on Coastal Zones in the EU and the Costs and Benefits of Adaptation*, in Watkiss, P. (ed.), The ClimateCost Project, Vol. 1, Stockholm Environment Institute, Sweden.

Brown, S., A.S. Kebede and R.J. Nicholls (2009), *Sea-Level Rise and Impacts in Africa, 2000 to 2100*, report prepared for the Stockholm Environment Institute.

Bruner, A., R. Naidoo and A. Balmford (2008), *Review on the economics of biodiversity loss: Scoping the science*, Review of the costs of conservation and priorities for action, European Commission, Brussels.

BUND (2011): URL www.bund-naturschutz.de/fileadmin/download/alpen

Burton, I. (2004), *Climate Change and the Adaptation Deficit*, in French, A. et al. (eds.), *Climate Change: Building the Adaptive Capacity*, Meteorological Service of Canada, Environment Canada.

Callaway et al. (2011b), *The economic impact of climate change on energy demand for space heating and cooling*. In: Assessing the economic impact of climate change. UNDP.

Callaway et al., (2011a), *The economic impacts of climate change on the hydro-electric sector: a case study of the Mavrovo hydro plant*. In: Assessing the economic impact of climate change. UNDP.

Callaway, J.M. et al. (2006), *The Berg River Dynamic Spatial Equilibrium Model: A New Tool for Assessing the Benefits and Costs of Alternatives for Coping With Water Demand Growth, Climate Variability, and Climate Change in the Western Cape*, AIACC Working Paper, No. 31, The AIACC Project Office, International START Secretariat, Washington, DC.

Callaway, John M. (2004), *Adaptation benefits and costs: are they important in the global policy picture and how can we estimate them?* Viewpoint. In: Global Environmental Change 14 (2004) 273-282 .

Carraro C. and A. Sgobbi (2008), *Climate Change Impacts and Adaptation Strategies in Italy: An Economic Assessment*, Available at: *http://ageconsearch.umn.edu/bitstream/6373/2/dp080006.pdf* (accessed March 2015).

Cartwright, A. et al. (2013), *Economics of climate change adaptation at the local scale under conditions of uncertainty and resource constraints: the case of Durban, South Africa*", Environment and Urbanization, No. 6, *http://dx.doi.org/10.1177/0956247813477814*.

CCRIF (Caribbean Catastrophe Risk Insurance Facility) (2010), *Enhancing the ClimateRrisk and Adaptation Fact Base for the Caribbean: An informational brochure highlighting the preliminary results of the ECA Study*, CCRIF's Economics of Climate Adaptation Initiative, Cayman Islands.

CEPS and ZEW (2010), *The Fiscal Implications Of Climate Change Adaptation*, Centre for European Policy Studies and Centre for European Economic Research, Brussels and Mannheim.

Chambwera, M. et al. (2014), *Economics of adaptation*. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

Chamen, W.C.T., Moxey, A.P., Towers, W., Balana, B., Hallett, P.D., (2015), *Mitigating arable soil compaction: A review and analysis of available cost and benefit data*. Soil Tillage Res. 146, 10–25. doi:10.1016/j.still.2014.09.011

Chiabai A and Spadaro J (2014), *Climate change adaptation and human health*. In Markandya A, Galarraga I, Sainz de Murieta E (Eds).Routledge Handbook on Economics of Adaptation. Routledge International Handbooks. Taylor and Francis. ISBN 978-0415633116.

Chiabai, A., Balakrishnan, S., Sarangi, G., and Nischal, S. (2010), *Human Health*. In Markandya A and Mishra A (Eds). Costing Adaptation: Preparing for Climate Change in India. TERI Press: New Delhi, India. ISBN 978-81-7993-388-6.

Ciscar, J.C. et al. (2011), *Physical and Economic Consequences of Climate Change in Europe*, PNAS, (Proceedings of the National Academy of Sciences), Vol. 108(7), *http://dx.doi.org/10.1073/pnas.1011612108*.

Ciscar, JC (ed.), Feyen, L., Lavalle, C., Soria, A. and Raes, F. (2014). Climate Impacts in Europe. The JRC PESETA II Project

City of Copenhagen (2012), *Københavns Kommunes Skybrudsplan 2012*, City of Copenhagen, Copenhagen.

Clements, J. (2013), *The Value of Climate Services Across Economic and Public Sectors*.

Climate Vulnerability Assessments. An Assessment of Climate Change Vulnerability, Risk, and Adaptation in Albania's Power Sector Climate Change in the United States. The prohibitive costs of inaction. Union of concerned scientists

Connor, J. et al. (2009), *Impacts of Climate Change on Lower Murray Irrigation*, Australian Journal of Agricultural and Resource Economics, Vol. 53(3), *http://dx.doi.org/10.1111/j.14678489.2009.00460.x*.

Considine, T.J. et al. (2004), *The value of hurricane forecasts to oil and gas producers in the Gulf of Mexico*, Journal of Applied Meteorology, 43, 1270-1281.

Contreras, R. and De Cuba, K. (2008), *The Potential impact of Climate Change on the energy sector in the Caribbean -region. An effort to understand how climate change may impact the productivity of* *existing and future energy production systems in the Caribbean*. Department of Sustainable Development Organization of American States.

Crowe K.A. and W.H.Parker (2008), *Using portfolio theory to guide reforestation and restoration under climate change scenarios*, Climatic Change, Vol. 89, *http://dx.doi.org/10.1007/s10584-007-9373-x*.

Darch, G., B. Arkell and J. Tradewell (2011), *Water resource planning under climate uncertainty in London*, Atkins Report 5103993/73/DG/035 for the Adaptation Sub-Committee and Thames Water, Atkins, Epsom.

de Ayala, A., Mariel, P., Meyerhoff, J., 2014. Transferring landscape values using discrete choice experiments: Is meta-analysis an option? Econ. Agrar. Recur. Nat. 14, 103–128. doi:10.7201/earn.2014.01.06

De Bel, M., A.H.H.M. Schomaker and F.C.J. van Herpen (2011), *Meerwaarde Levende Waterbouw: een maatschappelijke kostprijsanalyse*, Royal Haskoning in opdracht van Rijkswaterstaat Waterdienst.

de Bruin, K, (2012), *Investment in flood protection measures under climate change uncertainty*, Working Paper 2012:01, CICERO, Oslo, Norge, 51pp.

de Bruin, K. (2014), Annex A: Details on the Adaptation Funding Gap. In. UNEP (United Nations Environment Programme) (2014), *The Adaptation Gap Report 2014*, *www.unep.org/climatechange/ adaptation/gapreport2014/* (accessed 16 March 2015).

de Bruin, K. et al. (2009). Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change."

de Bruin, K. et al. (2009b), *Adapting to climate change in The Netherlands: An inventory of climate adaptation options and ranking of alternatives*, Climatic Change, Vol. 95(1-2), *http://dx.doi.org/10.1007/s10584-009-9576-4*.

de Bruin, K. et al. (2014), *Costs and benefits of adapting spatial planning to climate change: Lessons learned from a large-scale urban development project in the Netherlands*, Regional Environmental Change, Vol. 14(3), *http://dx.doi.org/10.1007/s10113-013-0447-1*.

de Bruin, K., R. Dellink and S. Agrawala (2009a), *Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits*, OECD Environment Working Papers, No. 6, OECD Publishing, Paris, *http://dx.doi.org/10.1787/225282538105*.

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41, 393–408. doi:10.1016/S0921-8009(02)00089-7.

de Lucena, A. F. P., Schaeffer, R., & Szklo, A. S. (2010). *Least-cost adaptation options for global climate change impacts on the Brazilian electric power system*. Global Environmental Change, 20(2), 342350.

de Lucena, A. F. P., Szklo, A. S., Schaeffer, R., & Dutra, R. M. (2010). *The vulnerability of wind power to climate change in Brazil*. Renewable Energy, 35(5), 904-912.

Defra (2011), *The UK Climate Change Risk Assessment (CCRA)*, UK Department for Environment, Food and Rural Affairs, London.

Dellink, R. et al. (2014), *Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment*, OECD Economics Department Working Papers, No. 1135, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz2bxb8kmf3-en*.

Delta Programme (2008), *Working together with water. A living land builds for its future*, Findings of the Deltacommissie, The Delta Programme, The Hague.

Delta Programme (2011), *Working on the delta: Investing in a safe and attractive Netherlands, now and in the future*, The Delta Programme, The Hague.

Delta Programme (2014), *Working on the delta: Promising solutions for tasking and ambitions*, The Delta Programme, The Hague.

Department of Energy and Climate Change (2013). *Estimated impacts of energy and climate change policies on energy prices and bills*.

Desbartes, J. (2012), *Adaptation Cost Assessment of Early Warning Systems and Implementing Measures*, Report as part of the EC Project *Methodologies for climate proofing investments and measures under cohesion and regional policy and the common agricultural policy*, IEEP.

Desjarlais, C. and C. Larrivée (2011), *Analyse économique de l'adaptation aux changements climatiques en matière de drainage urbain au Québec : comparaison de diverses stratégies d'adaptation pour un secteur de Montréal*, Consortium sur la climatologie régionale et l'adaptation aux changements climatiques, Canada.

Desjeux, G., L. Galoisy-Guibal and C. Colin (2005), *Cost-benefit analysis of vaccination against tick-borne encephalitis among French troops*, Pharmacoeconomics, Vol. 23(9).

Dessai, S., & Hulme, M. (2007). *Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England*. Global Environmental Change, 17(1), 59-72.

DFID (2014), *Early Value-for-Money Adaptation: Delivering VfM Adaptation using Iterative Frameworks and Low-Regret Options*, UK Department for International Development, London.

Dhakal, A. and A. Dixit (2013), *Economics of climate change in the water sector in Nepal. A stakeholderfocused approach. A case study of the Rupa Watershed, Kaski, Nepal. Project*: Economics of Climate Change in the Water Sector project, International Institute for Environment and Development (IIED), London, UK.

Di Falco, S. and M. Veronesi (2012), *How African Agriculture Can Adapt to Climate Change? A Counterfactual Analysis from Ethiopia*, Working Paper Series, No. 14, Department of Economics, University of Verona.

Doll, C., S. Klug, J. Köhler, I. Partzsch, R. Enei, V. Pelikan, N. Sedlacek, H. Maurer, L. Rudzikaite, A. Papanikolaou, V. Mitsakis (2011), *Adaptation Strategies in the Transport Sector. Deliverable 4 of the* *research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions)* funded under the 7th framework program of the European Commission.

Dore, M.H.I. and I. Burton (2001), *The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions*, a report prepared for the Climate Change Action Fund, Natural Resources Canada, Ottawa.

Doswald, N., Osti, M., 2011. Ecosystem-Based Approaches to Adaptation and Mitigation — Good Practice Examples and Lessons Learned in Europe. Federal Agency for Nature Conservation, Bonn, Germany.

Dowling, P., 2013. The impact of climate change on the European energy system. Energy Policy. Elsevier.

Downing, T. et al. (2011), *Planning and costing agriculture's adaptation to climate change: Policy Perspectives*, International Institute for Environment and Development (IIED), London, UK

Downing, T.E. (2012), *Views of the frontiers in climate change adaptation economics*, Wiley Interdisciplinary Reviews: Climate Change, Vol. 3(2), *http://dx.doi.org/10.1002/wcc.157*.

Droogers, P. (2009), *Climate Change and Hydropower, Impact and Adaptation Costs: Case Study Kenya*. Future Water Report 85, Future Water, Wageningen, Netherlands, 27 pp.

Dyszynski, J., Droogers, P., and Butterfield, R. (2009) *Climate adaptation economics: Kenya water sector*. Oxford, UK: Stockholm Environment Institute (SEI).

EA (2009a), *Thames Estuary 2100: Managing flood risk through London and the Thames estuary*, TE2100 Plan, Consultation Document, Environment Agency, Bristol.

EA (2009b), *Investing for the Future Flood and Coastal Risk Management in England: A Long-term Investment Strategy*, Environment Agency, Bristol.

EA (2009c), *Using science to create a better place: Ecosystem services case studies*, Environment Agency, Bristol.

EA (2011), *Thames Estuary 2100: Strategic Outline Programme*, Environment Agency (UK), Bristol.

EASPE (2002), *Use and Benefits of the National Weather Service River and Flood Forecasts*, National Hydrologic Warning Council, Denver.

Ebi, K.L. (2008), *Adaptation costs for climate change-related cases of diarrhoeal disease, malnutrition, and malaria in 2030*, Global Health, Vol. 4(9), *http://dx.doi.org/10.1186/1744-8603-4-9*.

Ebi, K.L. et al. (2004), *Heat Watch/Warning Systems Save Lives: Estimated Cost and Benefits for Philadelphia 1995-98*, Bulletin of the American Meteorological Society, *http://dx.doi.org/10.1175/BAMS-85-8-1067*.

ECA (2009), *Shaping climate-resilient development: A framework for decision-making*, a report of the Economics of Climate Adaptation working group, Economics of Climate Adaptation.

ECA (2009). Shaping climate-resilient development. A Framework for a decision making

ECLAC (2011a), *Review of the Economics of Climate Change in the Caribbean (RECC)*. Economic Commission for

ECLAC (2011b), *Assessment of the Economic Impact of Climate Change on the Coastal and Human Settlements Sector In Guyana*. Economic Commission for Latin America and the Caribbean (ECLAC).

ECLAC (2011c), *An assessment of the Economic Impact of Climate Change on the Health Sector in Saint Lucia*. Economic Commission for Latin America and the Caribbean (ECLAC).

ECLAC. (2011d) *An assessment of the economic impacts of climate change on the energy sector in Trinidad and Tobago*, ECLAC.

ECONADAPT (2015), *The Costs and Benefits of Adaptation*, results from the ECONADAPT Project, ECONADAPT consortium, *http://econadapt.eu/*.

EEA (2007), *Climate change: The cost of inaction and the cost of adaptation*, EEA Technical Report, No. 13/ 2007, European Environment Agency, Copenhagen.

EEA (2012). Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. European Environment Agency.

Eijgenraam, C., et al (2014). *Economically Efficient Standards to Protect the Netherlands Against Flooding*, Interfaces. Vol. 44(1), *http://dx.doi.org/10.1287/inte.2013.0721*.

Emerton, L., Baig, S., Saleem, M., 2009. Valuing Biodiversity: The Economic Case for Biodiversity Conservation in the Maldives (AEC Project). Ministry of Housing, Transport and Environment, Government of Maldives and UNDP Maldiv.

Environment Canada and Natural Resources Canada (2006), *Impacts of Sea Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick*.

EPA (2014). *The economic benefits of green infrastructure. A case study of Lancaster*, PA. 2012 EPA Green Infrastructure Technical Assistance Program.

Epstein, P. and E. Mills (2005), *Climate Change Futures: Health, Ecological and Economic Dimensions*, The Center for Health and Global Environment, Harvard Medical School.

Eskeland, G., S. and Mideksa, T., K. (2009). *Climate Change and Residential Electricity Demand in Europe*. Norwegian School of Economics and Business Administration and Centre for International Climate and Environmental Research-Oslo.

Evans, E. et al. (2004), *Foresight: Future Flooding*, Office of Science and Technology, London.

Fankhauser S. (1995) *Protection versus retreat: the economic costs of sea-level rise*. Environment and Planning A 27(2): 299-319.

FAO (2013), *Climate Smart Agriculture*, *www.climatesmartagriculture.org*, Food and Agriculture Organisation (accessed 28 April 2015).

FAO (2015), *Climate change and food systems: global assessments and implications for food security and trade*, Elbehri, A. (ed.), Food and Agriculture Organisation, Rome.

Farooq, M., Siddique, K.H.M., 2015. *Conservation Agriculture and Climate Change*, in: Conservation Agriculture.

Farooq, M., Siddique, K.H.M., 2015. Conservation Agriculture and Climate Change, in: Conservation Agriculture.

Faust, A. K., Gonseth, C., & Vielle, M. (2012). *The economic impact of climate driven changes in water availability in Switzerland*. In EcoMod 2012 (No. EPFL-CONF-177285).

Faust, A.K., C. Gonseth and M. Vielle (2012), *The economic impact of climate driven changes in water availability in Switzerland*, EciMod, No. 4277.

FDRE (2015), *Ethiopia's Climate-Resilience Strategy Agriculture*, Federal Democratic Republic of Ethiopia, Environmental Protection Authority.

Fedele, G., Vignola, R., Otarola, M., 2015. Ecosystem-based adaptation. Natural responses to climate change impacts, in: Chiabai, A. (Ed.), Climate Change Impacts on Tropical Forests in Central America: An Ecosystem Service Perspective, The Earthscan Forest Library. Routledge, Abingdon, pp. 190–210.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., Frayssinet, P., Bessemoulin, P., Laurent, F., De Crouy-Chanel, P., Jougla, E., Hémon, D. (2008), *Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave*. Int. J. Epidemiol. 37, 309–317. doi:10.1093/ije/dym253

Franco, G., and A.H. Sanstad. 2006. *Climate change and electricity demand in California*. Berkeley, CA: California Climate Change Centre.

Frontier Economics (2013), *The Economics of Climate Resilience CA0401*, Frontier Economics Ltd, Ecofys UK Ltd, Irbaris LLP, *www.frontier-economics.com/documents/2014/03/frontier-report-theeconomics-ofclimate-resilience-2.pdf* (Accessed 16 March 2015).

Fuss, S. et al. (2011), *Large-Scale Modelling of Global Food Security and Adaptation under Crop Yield Uncertainty*, Paper prepared for 2011 International Congress, August 30-September 2, 2011, Zurich, Switzerland, by European Association of Agricultural Economists, *http://purl.umn.edu/114347.*

Fuss, S. et al. (2015), *Global food security & adaptation under crop yield volatility*, Technological Forecasting and Social Change. *doi:10.1016/j.techfore.2015.03.019*.

Füssel H.M. and R.J.T. Klein (2006), *Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking*, Climatic Change, 75: 301-329.

Galarraga, I., Beristain Etxabe, I., Martín Landa, I., Boto Bastegieta, A., 2004. El método de transferencia de valor (benefit transfer), una segunda opción para la evaluación de impactos económicos: el caso del Prestige. Ekonomiaz 57, 30–45.

GCAP (Global Climate Adaptation Partnership) (2011), *The Economics of Climate Change in the United Republic of Tanzania*, a report prepared for the Development Partners Group and DFID.

Gersonius, B. et al. (2013), *Climate change uncertainty: Building flexibility into water and flood risk infrastructure*, Climatic Change, Vol. 116(2), *http://dx.doi.org/10.1007/s10584-012-0494-5*.

Glass, G.V., 1976. Primary, Secondary, and Meta-Analysis of Research. Educ. Res. 5, 3–8. doi:10.2307/1174772

Government of Tanzania (2014), *Agriculture Climate Resilience Plan (2014-2019)*, The United Republic of Tanzania, Ministry of Agriculture, Food Security and Cooperatives, Dar Es Salaam.

Groves, D.G. and C. Sharon (2013), *Planning Tool to Support Planning the Future of Coastal Louisiana*, Journal of Coastal Research, Special Issue 67, *http://dx.doi.org/10.2112/SI_67_10*.

Groves, D.G. et al. (2013), *Adapting to a Changing Colorado River. Making Future Water Deliveries More Reliable Through Robust Management Strategies*, Prepared for the US Bureau of Reclamation and conducted in the Environment, Energy and Economic Development Program within RAND Justice, Infrastructure and Environment, Santa Monica.

Haines, A., Kovats, R.S., Campbell-Lendrum D., and Corvalan, C., 2006. Climate Change and Human Health: Impacts, Vulnerability and Mitigatio, Lancet 367, 2101-2109.

Hallegatte, E., Hourcade, J. C. and Ambrosi, P. 2005. Using Climate Analogues for Assessing Climate Change Economic Impacts in Urban Areas. Kluwer Academic Publishers.

Hallegatte, S. et al. (2013), *Future flood losses in major coastal cities*, Nature Climate Change, Vol. 3, *http:// dx.doi.org/10.1038/nclimate1979*.

Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., Wood, R.M., 2011. *Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen*. Climatic Change 104, 113–137. doi:10.1007/s10584-010-9978-3

Hamilton, J.M., D. Maddison and R.S.J. Tol (2005), *Climate change and international tourism: A simulation study*, *Glob Environ Chang* 15(3):253-266.

Hawley, K., M. Moench and L. Sabbag (2012), *Understanding the economics of flood risk reduction: A preliminary analysis*, Institute for Social and Environmental Transition-International; Boulder CO.

Hinkel, J. and R.J.T. Klein (2009*), Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool*, Global Environmental Change, 19 (3): 384-395, *http://dx.doi.org/10.1016/ j.gloenvcha.2009.03.002*.

Hinkel, J. et al. (2010), *Assessing risk of and adaptation to sea-level rise in the European Union: An application of DIVA*, Mitigation and Adaptation Strategies for Global Change, Vol. 15, *http://dx.doi.org/10.1007/ s11027-010-9237-y*.

Hinkel, J. et al. (2013), *A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA*, Global Planetary Change, Vol. 111, *http://dx.doi.org/10.1016/j.gloplacha.2013.09.002*.

Hinkel, J. et al. (2014), *Coastal flood damage and adaptation costs under 21st century sea-level rise*, PNAS, Vol. 111(9), *http://dx.doi.org/10.1073/pnas.1222469111*.

HKV (HKV Consultants) and RPA (Risk Policy Analysts) (2014), *Study on Economic and Social Benefits of Environmental Protection and Resource Efficiency Related to the European Semester*, a report prepared for DG Environment.

HM Government (2013), *The National Adaptation Programme Report: Analytical Annex*, Economics of the National Adaptation Programme, HM Government, London.

Hochrainer-Stigler, S. et al. (2011), *The Costs and Benefits of Reducing Risk from Natural Hazards to Residential Structures in Developing Countries*, Working Paper, No. 2011-01, The Wharton School, University of Pennsylvania, Philadelphia.

Howden, M. et al. (2003), *An overview of the adaptive capacity of the Australian agricultural sector to climate change: options, costs and benefits*, Technical Report, CSIRO Sustainable Ecosystems, Canberra.

Hsai, E.C. et al. (2002), *Cost-effectiveness of the Lyme disease vaccine*, Arthritis Rheum, Vol. 46(6), *http:// dx.doi.org/10.1002/art.10270*.

Hughes, G., Chinowsky, P., & Strzepek, K. (2010). The costs of adaptation to climate change for water infrastructure in OECD countries. Utilities Policy, 18(3), 142-153.

Hughes, G., P. Chinowsky and K. Strzepek (2010), *The costs of adaptation to climate change for water infrastructure in OECD countries*, Utilities Policy, Vol. 18(3), *http://dx.doi.org/10.1016/j.jup.2010.03.002*.

Hunt (2011), *Policy Interventions to Address Health Impacts Associated with Air Pollution, Unsafe Water Supply and Sanitation and Hazardous Chemicals*, Environment Working Paper No. 35, OECD.

Hunt, A. & Watkiss, P. (2011). *Climate change impacts and adaptation in cities: a review of the literature*. Climatic change, 104, 13-49.

Hunt, A. and Anneboina, L. (2011*), Quantification and Monetisation of the Costs of Windstorms*, Deliverable 2D, ClimateCost project.

Hunt, A. and P. Watkiss (2010), *The Costs of Adaptation: Case Study on Heat Related Health Risks and Adaptation in London, Report under Specific Agreement under the Framework contract for economic support* (EEA/IEA/09/002) – Lot 2 “Climate change adaptation: costs and benefits”, Report to the European Environment Agency.

IBD and ECLAC (2014), *La economía del cambio climático en el Perú,* Inter-American Development Bank, and Economic Commission for Latin America and the Carribean Lima, *http://www.cepal.org/es/ publicaciones/37419-la-economia-del-cambio-climatico-en-el-peru* (accessed 20 April 2015).

ICF (2007), *The potential costs of climate change adaptation for the water industry*, Report submitted to UK Environment Agency, ICF International, London, UK.

IDS NEPAL, PAC and GCAP (2013). Economic impact assessment of climate change in key sectors in Nepal. IDS-NEPAL, Katmandu, Nepal

IDS-Nepal (Integrated Development Society Nepal), PAC (Practical Action Consulting) and GCAP (Global Climate Adaptation Partnership) (2014), *Economic Impact Assessment of Climate Change in Key Sectors in Nepal*, Integrated Development Society Nepal , Kathmandu.

IEA (2014). World Energy Investment Outlook. Special Report. International Energy Agency.

IFC (2011), *Climate Risk and Business: Ports – Terminal Marítimo Muelles el Bosque Cartagena, Colombia*, International Finance Corporation, Washington, DC.

Iglesias, A. et al. (2012), *Agriculture. The ClimateCost Project*, Final Report.

Ignaciuk, A. and D. Mason-D'Croz (2014), *Modelling Adaptation to Climate Change in Agriculture*, OECD Food, Agriculture and Fisheries Papers, No. 70, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jxr clljnbxq-en*.

IPCC (2007), *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York.

IPCC (2012), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York.

IPCC (2013), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York.

IPCC (2014), *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York.

Isaac, M. and D.P. van Vuuren (2009), *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*, Energy Policy, Vol. 37(2), *http://dx.doi.org/10.1016/ j.enpol.2008.09.051*.

Jeuland, M. and D. Whittington (2013), *Water Resources Planning under Climate Change: A 'Real Options' Application to Investment Planning in the Blue Nile*, Environment for Development. Discussion Paper Series, No. 13-5.

Jochem, E. and W. Schade (2009), *Adaptation and Mitigation Strategies Supporting European Climate Policy*, ADAM Deliverable D-M1.2, Fraunhofer Institute for Systems and Innovation Research, Munich.

Johnston, R.J., Rosenberger, R.S., 2009. Methods, trends and controversies in contemporary benefit transfer. J. Econ. Surv. doi:10.1111/j.1467-6419.2009.00592.x

Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. Harnessing nature to help people adapt to climate change. Nat. Clim Change 2, 504–509. doi:10.1038/nclimate1463

Jongman, B. et al. (2014), *Increasing Stress on Disaster-Risk Finance due to Large Floods*, Nature Climate Change, Vol. 4, *http://dx.doi.org/10.1038/nclimate2124*.

Jonkeren, O. (2009), *Adaption to climate change in inland waterway transport*, Vrije Universiteit.

JRC, EEA, 2010. The European Environment, State and Outlook 2010, Soil. European Commission, Joint Research Centre (JRC) and European Environment Agency (EEA), Luxembourg.

JRC, EEA, 2010. The European Environment, State and Outlook 2010, Soil. European Commission, Joint Research Centre (JRC) and European Environment Agency (EEA), Luxembourg.

Kettunen, M. (2011), *Water, ecosystem services and nature: putting the 'green' into green economy*, Paper presented at the Stockholm World Water Week, 23 August 2011, Stockholm.

Khabarov, N. et al. (2014), *Forest fires and adaptation options in Europe*, Regional Environmental Change, *http://dx.doi.org/10.1007/s10113-014-0621-0*.

Khanna, S. (2012) Impact of climate change on residential electricity consumption: evidence from weather fluctuations across building climate zones in California

Kind, J. M (2014). *Economically efficient flood protection standards for the Netherlands*. Flood Risk Management, 7 (2014) 103-117. *DOI: 10.1111/jfr3.12026*.

Kirshen, P. (2007), *Adaptation Options and Cost in Water Supply*, Report to the UNFCCC Secretariat, Bonn.

Kirshen, P. et al. (2005), *Global Analysis of Changes in Water Supply Yields and Costs under Climate Change: A Case Study in China*, Climatic Change, Vol. 68(3), *http://dx.doi.org/10.1007/s10584-0051148-7*.

Kirshen, P., Knee, K., & Ruth, M. (2008). Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies. Climatic Change, 90(4), 453–473. doi:10.1007/s10584-008-9398-9

Kirshen, P., McCluskey, M., Vogel, R. and Strzepek, K. (2005) 'Global analysis of changes in water supply yields and costs under climate change: a case study in China', Climatic Change 68(3): 303–330.

Kirshen. P. et al. (2004), *Climate's Long-term Impacts on Metro Boston (CLIMB)*, Final Report to the US EPA. Available at *http://dx.doi.org/10.1007/s10584-005-1148-7*.

Kiszewski, A.; Johns, B.; Schapria, A.; Delacollette, C.; Crowell, V.; Tan-Torres, T.; Ameneshewa, B.; Teklehaimanot, A.; Nafo-Traore, F. (2007). Estimated Global Resources Needed to Attain International Malaria Control Goals. Bulletin WHO 2007, 85, 623-630.

Klik, A., Eitzinger, J., 2010. Impact of climate change on soil erosion and the efficiency of soil conservation practices in Austria. J. Agric. Sci. 148, 529–541. doi:10.1017/S0021859610000158

Klik, A., Eitzinger, J., 2010. Impact of climate change on soil erosion and the efficiency of soil conservation practices in Austria. J. Agric. Sci. 148, 529–541. doi:10.1017/S0021859610000158

KMatrix (2014), *London's Adaptation Economy 2012/13*, Report to the Mayor of London.

Kontogianni, A. et al. (2013), *Assessing sea level rise costs and adaptation benefits under uncertainty in Greece*, Environmental Science & Policy, vol. 37, *http://dx.doi.org/10.1016/j.envsci.2013.08.006*.

Kovats, S., Lloyd. S., Hunt, A. & Watkiss, P. (2011). The impacts and economic costs of climate change on health in Europe. Technical Policy Brief Note 5: Health, ClimateCost project.

Kull, D., R. Mechler and S. Hochrainer-Stigler (2013), *Probabilistic cost-benefit analysis of disaster risk management in a development context*, Disasters, Vol. 37(3), *http://dx.doi.org/10.1111/disa.12002*.

Kundzewicz, Z.W. et al. (2014), *Flood risk and climate change: Global and regional perspectives*, Hydrological Sciences Journal, Vol. 59(1), *http://dx.doi.org/10.1080/02626667.2013.857411*.

Lähesmaa, J (1997). Kotka-Hamina sääohjatun tien yhteiskuntataloudellisuus. Tieliikenteen telematiikka – E18-kokeilualue.

Latin America and the Caribbean (ECLAC). *http://www.cepal.org/cgibin/getprod.asp?xml=/portofspain/*

Lazo, J.K. and D.M. Waldman (2011), *Valuing improved hurricane forecasts*, Economics Letters, Vol. 111(1), *http://dx.doi.org/10.1016/j.econlet.2010.12.012*.

Lazo, J.K., J.S. Rice and M.L. Hagenstad (2010), *Benefits of investing in weather forecasting research: An application to supercomputing*, Yuejiang Academic Journal, Vol. 2.

LCCP (2009), *Economic Incentive Schemes for Retrofitting London's Existing Homes for Climate Change Impacts*, London Climate Change Partnership, Published by Greater London Authority.

Leclère, D. et al. (2014), *Climate change induced transformations of agricultural systems: insights from a global model*, Environmental Research.Letters, Vol. 9(12), *http://dx.doi.org/10.1088/17489326/9/12/124018*.

Lehnera, B., Czischb, G. and Vassoloa, S. (2003). The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy. Elsevier.

Lempert, R.J. and D.G. Groves (2010), *Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west*, Technological Forecasting and Social Change, Vol. 77(6), *http://dx.doi.org/10.1016/j.techfore.2010.04.007*.

Lempert, R.J. et al. (2013), *Ensuring Robust Flood Risk Management in Ho Chi Minh City*, Policy Research Working Papers, No. 6465, World Bank, Washington, DC, *http://dx.doi.org/10.1596/1813-94506465*.

Liao, K.J. et al. (2010), *Cost Analysis of Impacts of Climate Change on Regional Air Quality*, Journal of the Air & Waste Management Association, Vol. 60(2), *http://dx.doi.org/10.3155/1047-3289.60.2.195*.

Linares, CG, Alfére,z RC, Díaz, JJ (2014). Análisis del impacto a corto plazo de los extremos térmicos y de otros factores ambientales sobre la mortalidad diaria en la ciudad de Madrid en el periodo 20012009: Causas específicas y Grupos de edad. Escuela Nacional de Sanidad. Informe final BASE Project FP7.

Liu, S., Costanza, R., Farber, S., Troy, A., 2010. Valuing ecosystem services. Annals of the New York Academy of Sciences 1185, 54–78. doi:10.1111/j.1749-6632.2009.05167.x

Lunduka, R.W. (2013), *Multiple stakeholders' economic analysis of climate change adaptation: A case study of Lake Chilwa Catchment, Malawi*, IIED, London.

Lunduka, R.W., Bezabih, M. and Chaudhury, A. (2012). Stakeholder-focused cost benefit analysis in the water sector: A synthesis report. International Institute for Environment and Development (IIED), London, UK.

Macauley, M.K. (2010), *Climate Adaptation Policy: The Role and Value of Information*, Issue Brief, No. 10-10, Resources for the Future, Washington, DC.

MacLeod, M., Moran, D., Eory, E., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Pete, S., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric. Syst. 103, 198–209.

MacLeod, M., Moran, D., Eory, E., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Pete, S., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric. Syst. 103, 198–209.

Máñez, M. and A. Cerdà (2014), *Prioritisation Method for Adaptation Measures to Climate Change in the Water Sector*, CSC Report 18, Climate Service Center, Germany.

Mansur et al, (2005). A Discrete-Continuous Choice Model of Climate Change Impacts on Energy.

Mansur, E.; Mendelsohn, R. and Morrison, W. (2007). Climate Change adaptation: a study of fuel choice and consumption in the US energy sector

Margulis, S. and C.B.S. Dubeux (2010), *Economia da Mudança do Clima no Brasil: Custos e Oportunidades*, IBEP Gráfica, São Paulo.

Markandya A and Chiabai A (2009). Valuing Climate Change Impacts on Human Health: Empirical Evidence from the Literature, International journal of Environmental Research and Public Health, Vol. 6(2): 759-786. DOI 10.3390/ijerph6020759, ISSN 1660-4601.

Markandya, A. and A. Mishra (eds.) (2010), *Costing Adaptation: Preparing for climate change in India*, The Energy and Resources Institute, New Delhi.

Markandya, A., I. Galarraga and E. Sainz de Murieta (eds.) (2014), *Routledge Handbook of the Economics of Climate Change Adaptation*, Routledge, Oxon and New York.

Martin, R., Gomes,C., Alleyne, D., Willard, P. (2013). An assessment of economic and social impacts of climate change on the energy sector in the Caribbean", Economic Commissions for Latin America and the Caribbean (ECLAC)

Martinez-Juarez, P., Chiabai, A., Taylor, T., Quiroga Gómez, S. (2015). "The impact of ecosystems on human health and well-being: A critical review". Journal of Outdoor Recreation and Tourism. Available online 29 July 2015. doi:10.1016/j.jort.2015.06.008.

Martin-Ortega, J. et al. (2012), *Cost-effectiveness analysis report for the Thame sub-catchment including analysis of disproportionality*. FP7 REFRESH Adaptive strategies to Mitigate the Impacts of Climate Change on European Freshwater Ecosystems. Deliverable 6.12.

Matiya, G., R. Lunduka and M. Sikwese (2011), *Planning and costing agricultural adaptation to climate change in the small-scale maize production system of Malawi*, International Institute for Environment and Development (IIED), London, UK, *http://pubs.iied.org/G03170.html* (Accessed 16 March 2015).

Maurer, H.; Rudzikaite, L., Kiel, J., et al. (2012): WEATHER Case studies – Synthesis Report; (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) funded under the 7th framework programme of the European Commission. Project co-ordinator: Fraunhofer-ISI. Karlsruhe, January 2012.

McCarl, B.A. (2007), *Adaptation Options for Agriculture, Forestry and Fisheries*, a report to the UNFCCC Secretariat, Financial and Technical Support Division.

McCarthy, N., L. Lipper and G. Branca (2011), *Climate-Smart Agriculture: Smallholder Adoption and Implications for Climate Change Adaptation and Mitigation*, Mitigation of Climate Change in Agriculture Series, No. 4, FAO, Rome.

McVittie, A., Ghaley, B.B., Andras, M., Camila, D., 2014. Deliverable 3.2 Report on Cost Effectiveness of SOC measures. Project SmartSoil, Sustainable farm Management Aimed at Reducing Threats to SOILs under climate change, European Commission.

McVittie, A., Ghaley, B.B., Andras, M., Camila, D., 2014. Deliverable 3.2 Report on Cost Effectiveness of SOC measures. Project SmartSoil, Sustainable farm Management Aimed at Reducing Threats to SOILs under climate change, European Commission.

Mechler, R. (2005), *Cost-benefit analysis of natural disaster risk management in developing countries*, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ). Arbeitskonzept, Eschborn, Germany.

Mechler, R. (2009), *The Cost-Benefit Analysis Methodology*, From Risk to Resilience Working Paper, No. 1, Moench, M., E. Caspari and A. Pokhrel (eds.), ISET, ISET-Nepal and ProVention, Kathmandu.

Mechler, R. (2012), *Reviewing the economic efficiency of disaster risk management*, Review Commissioned by Foresight Project: Reducing Risks of Future Disasters.Priorities for Decision Makers, IIASA, 2012.

Mechler, R. et al. (2014), *Making Communities More Flood Resilient: The Role of Cost Benefit Analysis and Other Decision-Support Tools in Disaster Risk Reduction*, White Paper, Zurich Flood Resilience Alliance.

Mendelshon, R and Morrison, W., N. (1999). The impact of global warming on US energy expenditures.

Menne, B. & Ebi, K. L. (2006). Change and adaptation strategies for human health, Springer.

Meteorological and Hydrological Services. Proceedings of the Technical Conference, Geneva, 26-30 March 1990; Thornes. JE (1990). *The development and status of road weather information systems in Europe and North America*. Proceedings of the WMO Technical Conference, WMO, Geneva, pp 204-214."

Metroeconomica (2006), *Climate Change Impacts and Adaptation: Quantify the Cost of Impacts and Adaptation*, Report to Defra, London.

Meyer, F et al. (2015). Economic evaluation of adaptation options. Deliverable 5.2 BASE Project FP7.

Michelon, T., P. Magne and F. Simon-Delaville (2005), *Lessons of the 2003 heat wave in France and action taken to limit the effects of future heat waves*, in Kirch, W., B. Menne and R. Bertollini (eds.), *Extreme Weather Events and Public Health Responses*, Springer-Verlag.

Mima, S., P. Criqui and P. Watkiss (2011), *The Impacts and Economic Costs of Climate Change on Enery in Europe: Summary of Results from the EC RTD ClimateCost Project*, in Watkiss, P. (ed.), *The ClimateCost Project*, Vol. 1, Stockholm Environment Institute, Sweden.

Mirasgedis, S. et al. (2006). Modelling framework for estimating impacts of climate change on electricity demand at regional level: Case of Greece. Energy Conversion & Management. Elsevier.

MMC (2005), *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*, Volume 2 – Study Documentation, Multihazard Mitigation Council, Washington, DC.

Moeltner, K., Boyle, K.J., Paterson, R.W., 2007. Meta-analysis and benefit transfer for resource valuation-addressing classical challenges with Bayesian modeling. J. Environ. Econ. Manag. 53, 250–269. doi:10.1016/j.jeem.2006.08.004

Moench, M. et al. (2009), *Rethinking the costs and benefits of disaster risk reduction under changing climate conditions*, in Moench, M. et al. (eds.), *Catalyzing Climate and Disaster Resilience*, ISET-Nepal, Kathmandu.

Moran, D. et al. (2013), *Research to assess preparedness of England's natural resources for a changing climate: Part 2 – assessing the type and level of adaptation action required to address climate risks in the 'vulnerability hotspots'*, Report to the Adaptation Sub-Committee of the Committee on Climate Change, United Kingdom.

Morel, C.M; Lauer, J.A.; Evans, D.B. (2005) *Cost Effectiveness Analysis of Strategies to Combat Malaria in Developing Countries*. BMJ Bri. Med. J. 331, 1299.

Morrison, W., & Mendelsohn, R. (1998). The impacts of climate change on energy: An aggregate expenditure model for the US (No. DOE/ER/61917--T1-Pt. 1). Yale Univ., School of Forestry and Environmental Studies, New Haven, CT (United States). Mosnier, A. et al. (2014), *Global food markets, trade and the cost of climate change adaptation*, Food Security, Vol. 6(1), *http://dx.doi.org/10.1007/s12571-013-0319-z*.

Muller, M. (2007), *Adapting to Climate Change: Water Management for Urban Resilience*, Environment and Urbanization, Vol. 19(1), *http://dx.doi.org/10.1177/0956247807076726*.

N.H. Ravindranath, P. Balachandra (2009). Sustainable bioenergy for India: Technical, economic and policy analysis. Energy 34 (2009) 1003–1013

Nadal, M., Schuhmacher, M., Domingo, J.L. 2009. Cost-benefit analysis of using sewage sludge as alternative fuel in a cement plant: a case study. Environ Sci Pollut Res Int, 16(3), 322-328

Nassopoulos, H., P. Dumas and S. Hallegatte (2013), *Adaptation to an Uncertain Climate Change: Cost Benefit Analysis and Robust Decision Making for Dam Dimensioning*, Climatic Change (2012) 114:497508, *http://dx.doi.org/10.1007/s10584-012-0423-7*.

Natural Disasters in Australia – Reforming mitigation, relief, and recovery arrangements; A report to the Council of Australian Governments by a high level officials‘ group, August 2002.

Naumann, S. et al. (2011), *Assessment of the potential of ecosystem-based approaches to climate change adaptation and mitigation in Europe*, Final report to the European Commission, DG Environment, Ecologic Institute, Berlin, and the Environmental Change Institute, Oxford University Centre for the Environment, Oxford.

NEA (2011). Market opportunities for fibreglass inland ships (in Dutch: Marktkansen voor Composiet Binnenvaartscheppen)

Nelson, G.C. et al. (2009), *Climate Change: Impact on Agriculture and Costs of Adaptation*, IFPRI, Washington, DC.

Nelson, J.P., Kennedy, P.E., 2009. The Use (and Abuse) of Meta-Analysis in Environmental and Natural Resource Economics: An Assessment. Environ. Resour. Econ. 42, 345–377. doi:10.1007/s10640-0089253-5

Neufeldt, H. et al., (2010), *Climate policy and inter-linkages between adaptation and mitigation*, Chapter 1. In. *Making Climate Change Work for Us. European perspectives of adaptation and mitigation strategies* (ADAM). Editors: Mike Hulme and Henry Neufeldt. Published by Cambridge University Press, 2010.

Neumann J., Price J., et al. (2014) Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage. Climatic Change: 1-13.

Neumann, J. et al. (2011), *The economics of adaptation along developed coastlines*, Wiley Interdisciplinary Reviews: Climate Change, Vol. 2(1), *http://dx.doi.org/10.1002/wcc.90*.

Niemi, E. 2009a. An overview of potential economic costs to New Mexico of a business-as-usual approach to climate change. Eugene, OR: Climate Leadership Initiative, University of Oregon.

NRC (Natural Resources Canada) (2007), *From Impacts to Adaptation: Canada in a Changing Climate,* Government of Canada, Ottawa.

NRTEE (2011), *Paying the Price: The Economic Impacts of Climate Change for Canada*, National Round Table on the Environment and the Economy, Ontario.

Nurmi, V. et al. (2013), *Cost-Benefit Analysis Of Green Roofs In Urban Areas: Case Study In Helsinki*. Finnish Meteorological Institute. Helsinki 2013. Available at https://helda.helsinki.fi/bitstream/handle/10138/40150/2013nro2.pdf?sequence=1 (Accessed March 2015).

OECD (2007), *Climate Change in the European Alps: Adapting Winter Tourism and Natural Hazards Management*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264031692-en*.

OECD (2008), *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264046214-en*.

Ojea, E., 2015. Challenges for mainstreaming Ecosystem-based Adaptation into the international climate agenda. Curr. Opin. Environ. Sustain. 14, 41–48. doi:10.1016/j.cosust.2015.03.006

Olonscheck, M., Holsten, A. and Kropp, J. P. (2011). Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy. Elsevier.

ONERC (2009), *Climate change: costs of impacts and lines of adaptation*, report to the Prime Minister and Parliament, Observatoire National sur les Effets du Réchauffement Climatique, Paris.

Ostro, B. et al. (2010), *The Effects of Temperature and Use of Air Conditioning on Hospitalizations*, American Journal of Epidemiology, 2010, Vol. 172, No. 9, *http://dx.doi.org/10.1093/aje/kwq231*.

Parry, M. et al. (2004), *Effects of climate change on global food production under SRES emissions and socio-economic scenarios*, Global Environmental Change, Vol. 14(1), *http://dx.doi.org/10.1016/j.gloenvcha.2003.10.008*.

Parry, M. et al. (2009), *Assessing the costs of Adaptation to climate change: A review of the UNFCCC and other recent estimates*, International Institute for Environment and Development and Grantham Institute for Climate Change, London.

Paul, B.K. (2009), *Why Relatively Fewer People Died? The Case of Bangladesh's Cyclone Sidr*, Natural Hazards, Vol. 50, *http://dx.doi.org/10.1007/s11069-008-9340-5*.

Pilli-Sihlova, K. et al. (2010), *Climate change and electricity consumption – Witnessing increasing or decreasing use and costs?*, Energy Policy, Vol. 38(5), *http://dx.doi.org/10.1016/j.enpol.2009.12.033*.

Pilli-Sihvola, K. et al. (2010). Climate change and electricity consumption—Witnessing increasing or decreasing use and costs? Energy Policy. Elsevier.

Pilli-Sihvola, Y, Toivonen, K, Kantonen, J (1993). Road Weather Service System in Finland and Savings in Driving Costs. Transportation Research Record 1387. Proceedings of the 3rd International Symposium on Snow Removal and Ice Control Technology, September 14-18, 1992, Minneapolis, Minnesota, pp. 196-200

Pohl, I. et al. (2014), *CBA Rotterdam Climate Adaptation Strategy – Case: Bergpolder Zuid*, consultancy report by REBEL to City of Rotterdam, Office for Sustainability and Climate Change. Rotterdam.

Porter, et al. (2014), *Food security and food production systems*. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Price, D. and K. Isaac (2012), *Adapting Sustainable Forest Management to Climate Change: Scenarios for Vulnerability Assessment*, Canadian Council of Forest Ministers, Ottawa.

Publications of Finnish Road Administration 36. (cited according to A. Papanikolaou, V. Mitsakis, K. Chrysostomou, C. Trinks, I. Partzsch (2011): —Innovative emergency management strategies‖ within the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) Deliverable 3, funded under the 7th framework program of the European Commission.)"

Ranger, N. and S.-L. Garbett-Shiels (2011), *How can decision-makers in developing countries incorporate uncertainty about future climate risks into existing planning and policy-making processes?*, Policy Paper, Grantham Research Institute on Climate Change and the Environment, London.

Ranger, N. et al. (2011), *An assessment of the potential impact of climate change on flood risk in Mumbai*, Climatic Change, Vol. 104, *http://dx.doi.org/10.1007/s10584-010-9979-2*.

Reid, H., Huq, S., 2005. Climate change – Biodiversity and livelihood impacts, in: Robledo, C., Kanninen, M., Pedroni, L. (Eds.), Tropical Forests and Adaptation to Climate Change: In Search of Synergies. Center for International Forestry Research CIFOR, Bogor, Indonesia, pp. 57–70.

RH DHV (2012), *Costs and Benefits of Sustainable Drainage Systems*, Report to the CCC by Royal Haskoning DHV.

Rickson, J., Deeks, L., Posthumus, H., Quinton, J., 2010. Understanding the costs and benefits of mitigation measures used to reduce or prevent soil erosion. (DEFRA Project SP1601), To review the overall costs and benefits of soil erosion measures and to identify cost-effective mitigation measures. Soil Functions, Quality and Degradation – Studies in Support of the Implementation of Soil Policy. DEFRA.

Rickson, J., Deeks, L., Posthumus, H., Quinton, J., 2010. Understanding the costs and benefits of mitigation measures used to reduce or prevent soil erosion. (DEFRA Project SP1601), To review the overall costs and benefits of soil erosion measures and to identify cost-effective mitigation measures. Soil Functions, Quality and Degradation – Studies in Support of the Implementation of Soil Policy. DEFRA.

Riksen, M., Brouwer, F., de Graaff, J., 2003. *Soil conservation policy measures to control wind erosion in northwestern Europe*. CATENA 52, 309–326. doi:10.1016/S0341-8162(03)00020-1

RMS (Risk Management Solutions) (2009), *Analyzing the Effects of the My Safe Florida Home Program on Florida Insurance Risk: RMS Special Report*, Risk Management Solutions Inc.

Rodrigues, G.C., Paredes, P., Gonçalves, J.M., Alves, I., Pereira, L.S., 2013. *Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation* *modelling: Ranking for water saving vs. farm economic returns*. Agric. Water Manag. 126, 85–96. doi:10.1016/j.agwat.2013.05.005

Rojas, R., L. Feyen and P. Watkiss (2013), *Climate change and river floods in the European Union: Socioeconomic consequences and the costs and benefits of adaptation*, Global Environmental Change, Vol. 23(6), *http:// dx.doi.org/10.1016/j.gloenvcha.2013.08.006*.

Rosenberger, R.S. and Stanley, T.D., (2006), Measurement, generalization, and publication: Sources of error in benefit transfers and their management. Ecol. Econ., Environmental Benefits Transfer: Methods, Applications and New DirectionsBenefits Transfer S.I. 60, 372–378. doi:10.1016/j.ecolecon.2006.03.018

Sainz de Murieta, E., Chiabai, A., Zamora, J.C., (2015), *Climate change impacts on water services in Costa Rica: A production function for the hydro-energy sector*, in: Chiabai, A. (Ed.), Climate Change Impacts on Tropical Forests in Central America: An Ecosystem Service Perspective. Routledge, Abingdon, UK, p. 224.

Sathaye, J., et al. (2011). Estimating risk to California Energy infrastructure from projected climate change. National Laboratory. University of California.

Scandizzo, P.L. (2011), *Climate Change Adaptation and Real Option Evaluation*, CEIS Working Paper, No. 232, *http://dx.doi.org/10.2139/ssrn.2046955*.

SCCV (Swedish Commission on Climate and Vulnerability) (2007), *Sweden facing climate change - threats and opportunities*, Ministry of the Environment and Energy, Stockholm.

SEI (Stockholm Environment Institute) (2009), *The Economics of Climate Change in East Africa*: Downing, T. et al. Report for DFID and DANIDA. Available at *http://kenya.cceconomics.org/*.

Seo, S.N. et al. (2009), *A Ricardian Analysis of the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa*, Environmental and Resource Economics, Vol. 43(3), *http://dx.doi.org/ 10.1007/s10640-009-9270-z*.

Settele, J. et al. (2014), *Terrestrial and inland water systems*. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.

Sgobbi, A. and C. Carraro (2008), *Climate Change Impacts and Adaptation Strategies in Italy: An Economic Assessment*, FEEM Fondazione Eni Enrico Mattei Research Paper; CMCC Research Paper, No. 14, *http:// dx.doi.org/10.2139/ssrn.1086627*.

Sieber, S., Pannell, D., Müller, K., Holm-Müller, K., Kreins, P., Gutsche, V., (2010). *Modelling pesticide risk: A marginal cost–benefit analysis of an environmental buffer-zone programme*. Land Use Policy 27, 653–661. doi:10.1016/j.landusepol.2009.08.021

Skourtos, M. et al. (2014), *Incorporating cross-sectoral effects into analysis of the cost-effectiveness of climate change adaptation measures*, Climatic Change, Vol. 128(3-4), *http://dx.doi.org/10.1007/s10584-014-1168-2*.

Skourtos, M., A. Kontogianni and C. Tourkolias (2013), *Report on the Estimated Cost of Adaptation Options Under Climate Uncertainty*, The CLIMSAVE Project – Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe, University of the Aegean, Greece.

Smith, K.R., A.Woodward, D. Campbell-Lendrum, D.D. Chadee, Y. Honda, Q. Liu, J.M. Olwoch, B. Revich, and R. Sauerborn, (2014). Human health: impacts, adaptation, and co-benefits. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel,A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

Stanton, E.A. and F. Ackerman. 2007. Florida and Climate Change: The Costs of Inaction. Global Development and Environment Institute, Tufts University and Stockholm Environment Institute–US Centre, Tufts University, Medford, MA (November).

Stanton, E.A., and F. Ackerman 2007. Florida and climate change: The costs of inaction. Medford, MA: Global Development and Environment Institute, Tufts University; and Stockholm Environment Institute.

Stanton, E.A., M. Davis and A. Fencl (2010), *Costing Climate Impacts and Adaptation: A Canadian Study on Coastal Zones*, a report commission by the National Round Table on the Environment and the Economy, Stockholm Environment Institute, Somerville.

Stapler, R.W., Johnston, R.J., 2008. Meta-Analysis, Benefit Transfer, and Methodological Covariates: Implications for Transfer Error. Environ. Resour. Econ. 42, 227–246. doi:10.1007/s10640-008-9230z

Stern, N. et al. (2006), *The Economics of Climate Change*, HM Treasury, London.

Subbiah, A., L. Bildan and R. Narasimhan (2008), *Background Paper on Assessment of the Economics of Early Warning Systems for Disaster Risk Reduction*, submitted to the World Bank Group, Global Facility for Disaster Reduction and Recovery, World Bank, Washington, DC.

Sussman, F. et al. (2014), *Climate change adaptation cost in the US: What do we know?*, Climate Policy, Vol. 14(2), *http://dx.doi.org/10.1080/14693062.2013.777604*.

Sutton, W.R., Srivastava, J.P., Neumann, J.E., Strzepek, K.M., Droogers, P., 2013. Reducing the Vulnerability of Albania's Agricultural Systems to Climate Change: Impact Assessment and Adaptation Options. The World Bank.

Sutton, W.R., Srivastava, J.P., Neumann, J.E., Strzepek, K.M., Droogers, P., 2013. Reducing the Vulnerability of Albania's Agricultural Systems to Climate Change: Impact Assessment and Adaptation Options. The World Bank.

Tainio, A. et al. (2014), *Conservation of grassland butterflies in Finland under a changing climate*, Regional Environmental Change, *http://dx.doi.org/10.1007/s10113-014-0684-y*.

Tanaka, S.K. et al. (2006), *Climate Warming and Water Management Adaptation for California*, Climatic Change, Vol. 76(3-4), *http://dx.doi.org/10.1007/s10584-006-9079-5*.

Taseska, V., Markovska, N. and Callaway, J.M. (2012). Evaluation of climate change impacts on energy demand. Energy 48 (2012) 88-95

TEEB (2009), *TEEB Climate Issues Update*, UNEP, Nairobi, *www.teebweb.org/media/2009/09/TEEBClimateIssues-Update.pdf* (accessed 26 February 2015).

TEEB (The Economics of Ecosystems & Biodiversity) (2010), *The Economics of Ecosystems and Biodiversity for Local and Regional Policy Makers*, Progress Press, Malta.

TEEB DE (2014), *Naturkapital und Klimapolitik – Synergien und Konflikte, Kurzbericht für Entscheidungsträger*, (Natural capital and climate policy - synergies and conflicts, Summary report for decision-makers), Technische Universität Berlin, HelmholtzZentrum für Umweltforschung – UFZ, Leipzig.

TEEB, 2010. The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations. Earthscan, London.

Teichmann, M. and A. Berghöfer (2010), *TEEBcase River Elbe flood regulation options with ecological benefits, Germany*, *www.teebweb.org* (accessed 26 February 2015).

Tol R. S. J. (2007), *The double trade-off between adaptation and mitigation for sea level rise: an application of FUND*. Mitigation and Adaptation Strategies for Global Change 12(5): 741-753.

Toloo, G., FitzGerald, G., Aitken, P., Verrall, K., Tong, S., 2013. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. Int. J. Public Health 58, 667–681. doi:10.1007/s00038-013-0465-2

Trenholm, R., Lantz, V., Martínez-Espiñeira, R., Little, S., 2013. Cost-benefit analysis of riparian protection in an eastern Canadian watershed. J. Environ. Manage. 116, 81–94. doi:10.1016/j.jenvman.2012.11.039

Trenholm, R., Lantz, V., Martínez-Espiñeira, R., Little, S., 2013. Cost-benefit analysis of riparian protection in an eastern Canadian watershed. J. Environ. Manage. 116, 81–94. doi:10.1016/j.jenvman.2012.11.039

Tri, N.H., Adger, W.N., Kelly, P.M., 1998. Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. Glob. Environ. Change 8, 49–61. doi:10.1016/S0959-3780(97)00023-X

Triple E Consulting (2014), *Assessing the Implications of Climate Change Adaptation on Employment in the EU*, Report to the European Commission, DG Climate Action.

Tröltzsch, J., H. Lückge and C. Sartorius (2012), *Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel: Analyse von 28 Anpassungsmaßnahme in Deutschland* [Costs and benefits of climate adaptation measures. Analysis of 28 adaptation measures in Germany]. Climate Change, No. 10/2012, UBA, Dessau.

UBA (2012): Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel: Analyse von 28 Anpassungsmaßnahme in Deutschland. (Costs and benefits of climate adaptation measures. Analysis of 28 adaptation measures in Germany). German Federal Environmental Agency (UBA), Climate Change Nr. 10/2012, Dessau.

UKCIP (UK Climate Impacts Programme) (2006), *Identifying adaptation options*, UKCIP, London.

UNDP (2011a), *Assessment of Investment and Financial Flows to Address Climate Change* (Capacity Development for Policy Makers to Address Climate Change). Country summaries. Available at: *www.undpcc.org/en/financial-analysis/results* (accessed 3 March 2015).

UNDP (2011b). Adaptation to climate change: an assessment of necessary investment and financial flows. Project "Capacity Development for Policy Makers to Address Climate Change".

UNEP (2014), *The Adaptation Gap Report 2014*, United Nations Environment Programme, *www.unep.org/ climatechange/adaptation/gapreport2014/* (Accessed 16.March.2015)

UNFCCC (2007), *Investment and Financial Flows to Address Climate Change*, United Nations Framework Convention on Climate Change, Bonn.

UNFCCC (2009), *Potential costs and benefits of adaptation options: A review of existing literature*, *FCCC/TP/ 2009/2*, United Nations Framework Convention on Climate Change, Bonn.

UNFCCC (2010), *Synthesis report on the National Economic, Environment and Development Study (NEEDS) for Climate Change Project*, *FCCC/SBI/2010/INF.7*, United Nations Framework Convention on Climate Change, Bonn.

US Department of Energy (2013) Effects of climate change on Federal Hydropower. Report to Congress. Washington, DC.

Vafeidis, A.T. et al. (2008), *A New Global Coastal Database for Impact and Vulnerability Analysis to SeaLevel Rise*, Journal of Coastal Research, Vol. 24(4), *http://dx.doi.org/10.2112/06-0725.1*.

van der Pol, T.D., E.C. van Ierland and H.P. Weikard (2013), *Optimal dike investments under uncertainty and learning about increasing water levels*, Journal of Flood Risk Management, Vol. 7(4), *http://dx.doi.org/ 10.1111/jfr3.12063*.

van Ierland, E.C. et al. (2006), *A qualitative assessment of climate change adaptation options and some estimates of adaptation costs*. Routeplanner subprojects 3, 4 and 5, Wageningen UR.

Vergara, W. et al. (2007), *Economic impacts of rapid glacier retreat in the Andes*, EOS Transactions American Geophysical Union, Vol. 88 (25), *http://dx.doi.org/10.1029/2007EO250001*.

Vergara, W.; Deeb, A. M.; Valencia, A. M.; Bradley, R. S.; Francou, B.; Zarzar, A.; Griinwaldt, A.; Haeussling, S. M. (2008): Economic Impacts of Rapid Glacier Retreat in the Andes. In: Eos, Vol. 88, No. 25, 19 June 2007, p. 261-264.

Vine, E. (2008) Adaptation of California's Electricity Sector to Climate Change, PPIC

Vivid Economics (2013), *The macroeconomics of climate change*, a report prepared for Defra, *www.vivid economics.com/index.php/publications/the-macroeconomics-of-climate-change* (accessed 2 March 2015).

Wang, X., Chen, D. and Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Building and Environment. Elsevier.

Ward, P.J. et al. (2010), *Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: A methodology and application*, Environmental Research Letters, Vol. 5(4), *http:// dx.doi.org/10.1088/1748-9326/5/4/044011*.

Watkiss, P. & Hunt, A. (2012). Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health. Climatic change, 112, 101-126.

Watkiss, P. (2011). The Impacts and Economic Costs of Climate change in Europe and the Costs and Benefits of Adaptation. ClimateCost Project. Final Report. Volume 1: Europe.

Watkiss, P. (ed.) (2012), *The ClimateCost Project*, Final Report, Volume 1: Europe, Stockholm Environment Institute, Sweden.

Watkiss, P. and A. Hunt (2010), *Review of adaptation costs and benefits estimates in Europe for the European Environment State and Outlook Report 2010*, Technical Report prepared for the European Environmental Agency for the European Environment State and Outlook Report 2010, published online by the European Environment Agency, Copenhagen.

Watkiss, P. and A. Hunt (2011), *Method for the UK Adaptation Economic Assessment* (Economics of Climate Resilience), *Final Report to Defra,* May 2011, Deliverable 2.2.1.

Watkiss, P. and A. Hunt (2014), *Low and no-regret adaptation – what do we know?*, ECONADAPT *http:// adaptationfrontiers.eu/pdf/B_U_03_PWatkiss.pdf* (accessed 16 March 2015).

Watkiss, P., Horrocks, L., Pye, S., Searl, A. & Hunt, A. (2009). Impacts of climate change in human health in Europe. PESETA-Human health study. European Commission: Joint Research Centre.

WHO (2009), *Improving public health responses to extreme weather/heat-waves – EuroHEAT*, Technical Summary, World Health Organisation Regional Office for Europe, Copenhagen.

WHO (2013), *Climate change and health: A tool to estimate health and adaptation costs*, World Health Organisation Regional Office for Europe, Bonn.

Wilby, R.L and R. Keenan (2012), *Adapting to flood risk under climate change*, Progress in Physical Geography, Vol. 36(3), *http://dx.doi.org/10.1177/0309133312438908*.

Wilhelm Geiger GmbH & Co. KG, Asphaltmischanlage Thanners: Preisliste, März 2011. http://www.aksellhofen.de/web/geiger_web.nsf/gfx/81AF0A2133647035C1257868002100A1/$file/Preisliste_AM A_Thanners_2011.pdf

World Bank (2006), *Clean Energy and Development: Towards an Investment Framework*, ESSD-VP/I-VP, April 5, 2006. Washington, DC, The World Bank.

World Bank (2009), *Evaluating Adaptation via Economic Analysis*, Guidance Note 7, Annex 12, World Bank,

World Bank (2010), *The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates*, The Global Report of the Economics of Adaptation to Climate Change Study, Synthesis Report, World Bank, Washington, DC.

World Bank (2010). The Costs to Developing Countries of Adapting to Climate Change: New Methods and Estimates. The Global Report of the Economics of Adaptation to Climate Change Study Consultation Draft. Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010: Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. Environmental Research Letters, 5(044011):10, 2010. doi: 10.1088/1748-9326/5/4/044011.

World Bank (2010b), *Mozambique – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2010c), *Ghana – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2010d), *Samoa – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2010e), *Ethiopia – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2010f), *Vietnam – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2010g), *Bangladesh – Economics of adaptation to climate change*, World Bank, Washington, DC.

World Bank (2011), *Natural Hazards, UnNatural Disasters: The Economics of Effective Prevention*, World Bank, Washington, DC. World Bank (2010), *Economics of Adaptation to Climate Change – Ecosystem Services*, Discussion Paper, No. 7, World Bank, Washington, DC.

World Bank (2012), *A Cost Effective Solution to Reduce Disaster Losses in Developing Countries: HydroMeteorological Services, Early Warning, and Evacuation*, World Bank, *Policy Research Working Paper* 6058, May 2012, World Bank, Washington, DC.

World Bank (2013), *Weather, Climate and Water Hazards and Climate Resilience: Effective Preparedness through National Meteorological and Hydrological Services*, World Bank, Washington, DC.

Wreford, A. and A. Renwick (2012), *Estimating the costs of climate change adaptation in the agricultural sector*, CAB Reviews, Vol. 7 (40), *http://dx.doi.org/10.1079/PAVSNNR20127040*.

Wright, L. et al. (2012), *Estimated effects of climate change on flood vulnerability of U.S. bridges*. Mitigation and Adaptation Strategies for Global Climate Change, 17, 939-955.

WTI (2009) (cited according to A. Papanikolaou, V. Mitsakis, K. Chrysostomou, C. Trinks, I. Partzsch (2011): ―Innovative emergency management strategies‖ within the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) Deliverable 3, funded under the 7th framework program of the European Commission.)"

Yohe G., Knee K., et al. (2011), *On the economics of coastal adaptation solutions in an uncertain world*. Climatic Change 106(1): 71-92.

Zachariadis, T. (2010), *Forecast of electricity consumption in Cyprus up to the year 2030: The potential impact of climate change*, Energy Policy, Vol. 38(2), *http://dx.doi.org/10.1016/j.enpol.2009.10.019*.

Zachariadis, T. and Hadjinicolaou, P. (2014). *The effect of climate change on electricity needs: A case study from Mediterranean Europe*. Energy 76 (2014) 899-910

Zahlen_Fakten_Bergwald_Alpen.pdf"UIC (2009): ERMTS Implementations Benchmark, Final Report, September.

Zhou, F. et al. (2007), *Potential climate change-induced permafrost degradation and building foundations: An assessment of impacts and costs for five case communities in the Northwest Territories*.

Zhu, X. et al. (2013), *A model-based assessment of adaptation options for Chianti wine production in Tuscany (Italy) under climate change*, Regional Environmental Change, *http://dx.doi.org/10.1007/s10113-014-0622-z*.

Notes:

[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 are entirely those of the study team and do not necessarily reflect the views of IDRC.