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The Economics of Adaptation

Concepts, Methods and Examples

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A guide for practitioners to assess economic benefits and costs of avoiding climate change damages through adaptation by developing these estimates using existing tools and data.

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Abbreviations

ANPV	Annualized Net Present Value
AS	Arabian Sea
BCA	Benefit Cost Analysis
BoB	Bay of Bengal
CGE	Computable General Equilibrium Models
CS	Consumer surplus
CS	Cyclonic Storm
CT	Conventional Tillage
DD	Deep Depression
EC	The European Commission
EC	Commission of the European Communities
EV	Expected Value
EVI	Expected Value of Information
EVPI	Expected Value of Perfect Information
EVUPI	Expected Value Under Perfect Information
FC	Fixed Costs
GCM	General Circulation Models
IAM	Integrated Assessment Model
IPA	Indian Ports Association
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
IWGSCC-USGOV	Interagency Working Group on Social Cost of Carbon, United States Government
LDC	Least Developed Countries
LRMC	Long-Run Marginal Cost
LRTC	Long-Run Total Cost
LRVC	Long-Run Variable Cost
MT	Minimum Tillage
MVP	Marginal Value Products

NAP	National Adaptation Program
NPV	Net Present Value
OECD	The Organisation for Economic Co-operation and Development
PE	Partial Equilibrium
PS	Producer Surplus
RCM	Regional Climate Models
RCP	Representative Concertation Pathways
RDM	Robust Decision Making
RWH	Rain Water Harvesting
SCAP	Storage Capacity
SCS	Severe Cyclonic Storm
SDR	Sustainable Development Reserves
SDS	Secretaria de Estado do Meio Ambiente e Desenvolvimento Sustentável
SOA	State-of-the-Art
SRES	The Special Report on Emission Scenarios
SRMC	Short-Run Marginal Cost
SRTC	Short-Run Total Cost
SRVC	Short-Run Variable Cost
STCAP	Storage Capacity - Optimal
SuCS	Super Cyclone
UDP	UNEP-DTU Partnership
UKCIP	UK Climate Impact Programme
UNDP	United Nations Development Program
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
URC	UNEP-Risø Center
USD	United States Dollar
VC	Variable Costs
WTP	Willingness to Pay
ZT	Zero Tillage

Foreword

Adaptation is increasingly at the forefront of climate change discussions and action. We see this reflected in the Paris Agreement adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change. We see it in the high prominence of adaptation in national and sectoral level strategies, plans and policies. Furthermore, we see it at the local level, where people are already adapting to the early impacts of climate change that affect livelihoods through, for example, changing rainfall patterns, drought, and frequency and intensity of extreme events.

Analyses of the costs and benefits of climate change impacts and adaptation measures are important to inform future action. Despite the growth in the volume of research and studies on the economics of climate change adaptation over the past 10 years, there are still important gaps and weaknesses in the existing knowledge that limit effective and efficient decision-making and implementation of adaptation measures. Much of the literature to date has focussed on aggregate (national, regional and global) estimates of the economic costs of climate change impacts. There has been much less attention to the economics of climate change impacts and the costs and benefits of adaptation measures at local level, where the impacts of climate change will manifest themselves, and where many adaptation actions need to be taken.

In our engagement with partners in developing countries, the need for a better understanding of the fundamentals of the economics of climate change adaptation and, in more practical terms, the need to understand the simplified methods used in assessing the costs and benefits of adaptation actions, have been stressed repeatedly. This publication is an attempt to address this need.

The publication deals with ways of elaborating the fundamentals of economics of climate change adaptation. It then goes on to the current bottom-up approaches that aid decision-makers in assessing the costs and benefits of adaptation actions. The technical report has three prominent components, dealing respectively with theoretical concepts, practical examples and decision-making under uncertainty. In addition, it provides a rich list of references for further research.

Our members of staff from different areas of specialization have contributed to this technical report. Our hope is that its comprehensive approach will be useful for those who are trying to bridge theory with practice and the decision-makers who design and implement adaptation policies.

Anne Olhoff

Drip irrigation system in raised garden bed

1. Introduction

John MacIntosh Callaway, Jr.

This introduction is a combination of an executive summary and an introduction to this report. However, it is organized more around ideas and concepts than it is around the chapters themselves. It attempts to weave together several aspects of the economics of adaptation to climate change into a cohesive whole. These aspects include, in very broad terms:

- A strictly economic definition of adaptation,
- The role of capital investment in adaptation, and
- The need to further build the technical capacity of local experts in many developing countries to assess the various economic costs and benefits associated with adaptation to climate change.

Over the years, researchers in many fields and policy-makers in a number of multi- and bi-lateral donor organizations have adopted various definitions of adaptation to climate change, as well as different classifications, in an effort to qualitatively distinguish among different forms of adaptation. A number of these are presented in the first part of Chapter 2. Among these classifications, perhaps the most widely used is the separation of adaptation into an autonomous part and a strategic, or "planned", part. Economists frequently use the term "autonomous adaptation" to refer to adaptation that is market-driven and then back this up empirically with various forms of market models to show how rational economic agents can be expected to react to the exogenous introduction of either meteorological variables or the physical impacts of these variables on economic activities to reflect climate change. However, this practice leaves the impression that in economic terms all, or almost all, adaptation to climate change, if not autonomous, is the result of rational behavior. Examples of planned adaptation in the economic literature generally take the form of investments in infrastructure to make people, places and things less vulnerable to climate change, the best example being the building of dikes, sea walls and other types of barrier to protect large population centers from sea-level rise. However, studies of these measures have, over time, adopted the practice of measuring the damage avoided by these structures, comparing them to the cost of building and maintaining them, and then signaling out those that perform best based on various benefit-cost criteria, not only on the basis of market values, but also in terms of environmental damage, as well as benefits, such as using mangrove forests to protect against tidal surges that will be exacerbated by sea-level rise and increases in the frequency and intensity of storms.

Our point here is to suggest that for economists it is difficult to untangle autonomous from planned adaptation. Both are the result of planning. What differs is the time span over which the planned activity operates and, to a certain extent, the amount of money involved in planning, building, operating, and maintaining investments in infrastructure.

Thus, in Chapter 2 we offer the following economic definition of adaptation to climate change: "adjustments in resource allocation that economic agents make in their consumption, production and investment decisions to avoid the economic losses, or to increase the economic gains, that are due directly or indirectly to the effects of climate change". At the same time, we dismiss the notion of autonomous and planned adaptation as a conceptually unhelpful dichotomy and look more carefully in Chapter 2 at the distinction between short- and long-run adaptation.

In the remainder of Chapter 2, we define a set of important economic metrics for measuring the various costs and benefits of adaptation to climate change and then develop an economic framework for explaining short- and long-run adjustment to climate change. Briefly stated, these metrics are:

Climate change damages: the economic value of the physical damages caused by climate change compared to a "business-as-usual (BAU)" scenario (without climate change and with existing technology and management practices used to cope with natural variability of climate);

Net benefits of adaptation: the economic value of the climate change damages avoided by means of the introduction of technology and management practices for adapting to climate change minus the real cost of the resources required to avoid these damages; and

Residual climate change damages: the economic value of the climate change damages that are not avoided by adaptation.

The economic framework in which these terms can be applied is explained fairly rigorously using production theory for households and firms in Chapter 2. This was thought necessary to untangle short-run from long-run adaptation. However, the general results and what they add to the existing treatment of adaptation in the literature are easier to state. The difference in short- and long-run adaptation in economic terms can be boiled down into a three-step adjustment process. In the first step, economic activities take a hit from climate change over which they have no control, but to which they can make an initial adjustment to their short- and long-run total cost and supply curves. For many different types of production functions, and under certain conditions described in the text, this will result in short- and long-run supply curves along which marginal and total costs are higher than before (i.e., without climate change) for a given level of output. Moreover, if planned production levels are optimal (i.e., least cost at an intersecting point in the short- and long-run supply curves) without climate change, the shift in the long- and short-run supply curves will preserve this optimality, such that there is no change in the quantities of variable inputs and the quasi-fixed capital input. However, output decreases. This will be called "the pure effect of climate change" (Callaway, 2014).

This new point of production is optimal from the standpoint of production, but not the market. The second step involves short-run adaptation, which consists of movements from the point where the pure effect of climate occurs, along the short-run supply curve, until a short-run market equilibrium is achieved at a higher level of output, a higher market price, a higher marginal production costs and a higher level of total economic welfare than at the start of this step. The third step, long-run adaptation, is an alternative to the second step and involves movements from the same starting point along the long-run supply curve until a long-run market equilibrium is achieved at a still higher level of output but lower marginal cost than in the case the short-run market equilibrium. Moreover, the level of total welfare will be higher than for the short-run equilibrium, but lower than at the original equilibrium point without climate change. This approach makes it possible to theoretically define the three economic metrics in terms of these adjustments, starting from the pure effect of climate change. Finally, we also add a fourth step at the end of Chapter 2, which involves changing the structural aspects of the production technology at some point to achieve even higher levels of outputs and welfare. We conclude by suggesting that one goal in designing new technology, especially in the case of infrastructure, is to do so in a way that incorporates a great deal of operational (i.e., short-run) flexibility in the long-run design. Doing this will help to improve the robustness of the infrastructure over a number of different climate outcomes in the face of "deep uncertainty", a topic taken up in Chapter 5. The tie-in between the analyses in Chapters 2 and 5 helps to resolve an obvious question arising from the welfare comparison between short- and long-run adaptation, namely: why remain in the short-run (step 2), if long-run adaptation results in higher net welfare? The answer is that, given the deep uncertainty associated with current climate change projections, betting on long-run adaptation involves a currently non-quantifiable risk in the face of large capital costs, and some investors will undoubtedly base their choice of short- vs. long-run adaptation on the maximum, "better to accept the risks you know than the ones you don't know".

Deep uncertainty arises out of ambiguity and disagreement among analysts and decision-makers, as well as a lack of information on the models that describe interaction among the system's variables, probability distributions representing uncertainty, and assessments of the appropriateness of alternative outcomes (Lempert et al., 2006). Practically, this means that, while a large and fast-growing data base of climate projects exists, we not only lack the information to characterize the partial and joint distributions of the random variables that affect the variability within and between the various climate outcomes, we also don't fully understand and find it hard to quantify the non-stochastic sources of the variability in climate outcomes caused within and between climate models. This leaves researchers and policy-makers with an abundance of climate change projections, but no really systematic way to assign probabilities to any of these outcomes, except on an ad-hoc basis, the current default being the uniform distribution.

Given a situation in which traditional methods of analyzing risk break down, a number of researchers have turned to a new approach, called Robust Decision Making (RDM). According to the Rand Corporation, "Robust decision making is an analytic framework that helps identify potential robust strategies, characterize the vulnerabilities of such strategies, and evaluate trade-offs among them."[1] This approach stands conventional ex-ante planning on its head by first identifying and developing adaptation strategies, analyzing the robustness of these strategies over a number of projected climate outcomes, and then, in typical cases, iterating the strategies or infrastructure designs in concert with stakeholders and policy-makers to find the most acceptable solution. In the last section of Chapter 5 we use a somewhat similar approach, namely a two-stage model that incorporates both long-run (investment) and short-run (operational) decisions, to explore the sources of robustness in a two-stage (ex-ante, ex-post) planning model using the metrics of climate change damages, economic regrets and the net benefits of additional adaptation. While the optimization models and example used to do this were very much simplified, two potential sources of robustness were observed in conjunction with non-parametric decision criteria.

The first potential source of the variation in the magnitude of net welfare lies in the economic value of climate change damages. The issue here has to do with how well an initial investment operates once it has been made and capital has been committed. An investment with built-in operational flexibility will presumably both meet its operational goals and produce higher net welfare over a large range of foreseeable climates than one that is designed to be optimal for a single climate outcome. However, this is not necessarily true of investments made in the face of a current climate that is highly variable, where high variability in the current climate may overlap with some projected climate states. A suggested decision criterion is to minimize the mean of climate change damages over a number of climate projections (if possible by also taking into account the variability of the welfare outcomes). The second source of variation lies in the value of economic regrets (or its alternative, the net benefits of adaptation) that are associated with further investments, for example, project staging over time. Thus, if climate change damages remain high over an initial investment (or business-as-usual investment), it may be possible to design the original investment so that additional investment to enhance its flexibility can be made at relatively low cost. Since minimization

1 http://www.rand.org/topics/robust-decision-making.html

of the economic regrets of additional adaptation turns out to be the negative value of maximizing the net benefits of additional adaptation, the outcome of either metric is whether or not building more operational flexibility into an existing investment is economically feasible. Finally, it is also possible to consider using the minimization of the residual climate change damages as a decision criterion, as this metric is the sum of climate change damages and the net benefits of adaptation. However, using this approach ignores the partial contribution of, and the interaction between, the two components.

The final strand we wanted to tie together using an economic definition of adaptation to climate change and the role of short- and long-run adaptation to climate is not substantive, but still may be the most important of the three. This involves the need to further build the technical capacity of local experts in many developing countries to assess the various economic costs and benefits associated with adaptation to climate change. The experience of the authors and of many of our colleagues is that developing countries often have well-trained experts who are capable of conducting economic evaluations of both mitigation and adaptation policies and projects, but that for some reason it is difficult for them to apply their economic skills to "unconventional" topics, such as adaptation to climate change. This should not seem very surprising to economists in many developed countries, who watched as well-trained engineers and researchers in other disciplines in the West re-invented neo-classical economics to evaluate climate change impacts and adaptation. The same message needs to be taught in many developing countries: there is nothing new in applying "traditional" economic thinking and methods to monetize the benefits and costs associated with adaptation to climate change (with the possible exception of deep uncertainty). Indeed, that is partly the lesson of Chapter 2.

However, there are other problems that have to be surmounted, especially in the Least Developed Countries (LDCs). The three most severe of these are:

- The lack of disciplinary connections to what is currently the state-of-the-Art (SOA) and its practitioners: This often has unanticipated, adverse consequences when multi- and bilateral organizations farm out research contracts to groups of international experts, who sometimes undertake local studies covering the impacts of adaptation to climate change with their own models and data bases, but without any real collaboration with local experts. By the same token, quite a few local experts whose higher education is funded by some of the same institutions never return to their country of origin to mentor local experts, although those who do or who continue to spotlight their research on their home countries make valuable contributions to the technical capacity of local experts.
- The lack of SOA analytical tools to estimate the costs and benefits associated with climate change adaptation: This is certainly true when it comes to more sophisticated economic methods and models, although they may not be needed at this point. This problem tends to be more pressing when it comes to the software required to simulate the physical impacts of climate change, the results of which can be used to create economic damage functions. Cases also come to mind where individuals working in various impact areas have received training for a specific piece of commercial software to simulate physical impacts and later left their institution, leaving no institutional memory of the whereabouts of, or how to use, the software. At the same time, the fragmentation of institutional co-operation often prevents local economists from knowing about and collaborating with highly skilled researchers in other fields who have developed their own models that work well with local data.
- Data poverty: This may be more of a state of mind than of fact. What is true is that SOA global databases that have been developed in the West that also cover developing countries, but are often not present in developing countries, nor are the models and human capital that can put these databases to use. However, as mentioned above, it is often the case that local experts know a lot about local data (and its quality) in their fields of expertise and have put it to good use. Nonetheless, since all of these issues are related, the further development of institutional capacity at the research

level is still required to bring together human capital in a variety of disciplines, their local models and databases to contribute successfully to economic evaluations of the physical impacts of, and adaptation to, climate change.

There are also a host of other problems related to institutional capacity that are too numerous and varied to generalize about in this report. However, they hamper the development of the technical capacity of local experts to estimate the benefits and costs associated with climate change impacts and adaptation to climate change. An example where this was not entirely the case was in Macedonia, where their National Academy of Science was closely connected with several ministries that were involved in energy and natural resource management, and also in close collaboration with the United Nations Development Program (UNDP). The results of this collaboration led to further collaboration between the UNEP-DTU Partnership, UNDP and a number of highly talented local researchers on a number of case studies to monetize climate change damages and the net-benefits of adaptations using local data and models (see Callaway et al., 2011).

All of these issues are addressed in one form or another in Chapters 2, 3, 4 and 5. Chapter 2 does so by providing an introduction to the question “What is adaptation to climate change?”, where we show that, from the standpoint of economic theory, short- and long- run adaptation are not any different in their economic properties than adjustments to air pollution and water pollution and other forms of local adjustment to exogenous changes in environmental quality over which households and firms have no direct control.[2] It also introduces the underlying economic metrics of climate change damages, the net benefits of adaptation and residual climate change damages used throughout this report.

Chapter 3 follows in this same vein by presenting a simplified, bottom-up approach to estimate these metrics in local case studies. This approach is hard to define in specific terms because it can take many forms. But, generally speaking, it involves using locally available data to outline the main technical and cost characteristics associated with different soft or hard technologies and/or management strategies to avoid current and/or future damages from climate change and/or climate variability. Damage functions, taken from available impact models or studies, are used to determine the effects of climate change/variability on the output of the economic activity that is affected by climate and/or on fixed and variable costs. Marginal economic values (prices) for outputs are based on currently observed prices and can be varied through sensitivity analysis. All this information is organized into an accounting framework on a spreadsheet such that different climate scenarios can be used to simulate the effects of climate on production and on an appropriate net welfare metric under different adaptation options. This information is used to calculate climate change damages, the net benefits of adaptation and the residual climate change for each adaptation alternative or combination of them. The analysis can be done in either a static or a dynamic framework and in a deterministic or stochastic framework, using available Monte Carlo simulation methods built into the spreadsheet software. The approach is best suited to assessing adaptation options in the private sector, but as long as enough information is available about the economic returns associated with ecosystem services and other forms of non-market activity, this approach can also be used to assess the economic worthiness of adaptation options in a non-market setting. It can also deal with the issue of technology externalities, as is illustrated in the last part of the rainwater harvesting example in Chapter 3 to account for the effects of diverting “virgin” water from a catchment on downstream water-users.

The simplified bottom-up approach is also followed in Chapter 4 with four more examples covering the adoption of conservation tillage in Tanzania, increasing the size of protected areas in the Brazilian Amazon to offset deforestation, protecting costal population centers from cyclones in the Bay of Bengal, and using

2 However, local, state and national governments may be able to formulate compensatory or regulatory policies, since these externalities are not global, but rather originate from local or trans-boundary sources.

beach nourishment to increase tourism revenues in a hypothetical LDC setting. All of these adaptation activities yield both development- and adaptation-related benefits. As such, the beach nourishment example shows why and how it is necessary to add a conventional benefit-cost analysis to the analysis of adaptation-related benefits and costs.

Hopefully, while the objectives of this report jump around a bit from chapter to chapter, developing country researchers can benefit from the information and synthesis we have provided. More examples of the bottom-up approach, both for estimating climate change damages and in the wider framework of adaptation costs and benefits, can be found in two studies completed for UNDP in Montenegro and Macedonia.[3] These two reports were the result of collaborations between UNDP, the UNEP-Risø Center (URC),[4] and local researchers in these two countries. The two projects were organized in the same way. UNDP and URC staff met at the start of each project to identify local experts, primarily economists and engineers. URC staff and the local researchers worked together to develop case studies and relevant methodologies in sectors identified by the local experts. In the process, a great deal of attention was paid to the availability of existing local data and models to execute the methodology. Important assumptions and short-cut methods for working around data gaps were identified and agreed upon. During the course of both projects, the local experts and URC staff reconvened to review work progress and to resolve data and methodological issues. Draft final reports for the case studies were prepared by the local experts and reviewed by URC staff and UNDP. The finished products were published as UNDP reports. A central unifying theme of these case studies was that all of them used the economic metrics identified in Chapters 2 and 3 to estimate climate change damages (in the case of impact studies), the net benefits of adaptation, and the residual climate change damages.

In Chapter 6, we recommend that this approach be extended to LDCs and other developed countries that lack the technical capacity, but not the required basic skills, to undertake economic analyses of adaptation policies and projects in their countries.

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4 URC has since been renamed the UNEP-DTU Partnership (UDP).

Sandbags outside front door of flooded house

2. Adaptation to Climate Change: Definitions, Concepts and Relevant Economic Metrics

John MacIntosh Callaway, Jr.

The objectives of this chapter are, first, to provide a definition of adaptation that is relevant to the discipline of economics; second, to explain the conceptual basis for this definition; and finally, to define the economic metrics that are relevant to assessing the benefits and costs of adaptation. Finally, the chapter analyses adaptation in the framework of short- and long-run adjustments to climate change.

Definitions of Adaptation

Let us look first at existing definitions of adaptation and different types of adaptation, and then use the insights and shortcomings of these definitions to provide not only an economic definition of adaptation to climate change, but also a conceptual overview of how humans, both singly and collectively, adapt to climate change, thus unifying many of the different types of adaptation into a single economic framework.

Official Definitions of Adaptation

As recently as 2007, the Intergovernmental Panel on Climate Change (IPCC) defined adaptation to climate change as "adjustments in natural and human systems in response to actual or expected climate stimuli or their effects, which moderate harm or exploit beneficial opportunities" (IPCC, 2007). The European Commission (EC) has adopted a very similar definition, namely "anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause, or taking advantage of opportunities that may arise (EC, 2007)"[5] For the United Nations Development Program (UNDP) adaptation "is a process by which strategies to moderate, cope with and take advantage of the consequences of climatic events are enhanced, developed, and implemented" (UNDP, 2005). According to the UK Climate Impact Programme, adaptation to climate change is "the process or outcome of a process that leads to a reduction in harm or risk of harm, or realization of benefits associated with climate variability and climate change" (UKCIP, 2003).

Over time, various researchers and public bodies have broken down adaptation into different types, based on various dimensions of adaptation. The most well-known of these, which generally come in opposing pairs, include:

- *Autonomous adaptation*, "a non-conscious response to climatic stimuli" (Malik et al., 2010) triggered by changes in natural systems or by economic market signals, vs. *Planned adaptation*, which is the result of deliberate planning.
- *Private adaptation*, undertaken by individuals, households and firms in the private sector, vs. *Public adaptation*, initiated and/or implemented by public bodies.

5 Access on line: http://ec.europa.eu/clima/policies/adaptation/index_en.htm

- *Anticipatory adaptation,* which includes actions to avoid, or to take advantage of, the impacts of climate change before they occur, vs. *Reactive adaptation*, which only takes place after the impacts have occurred.
- *No-regrets adaptation*, which is generally taken to mean actions that are taken for other reasons than adapting to climate change, but which also have beneficial effects if the climate does change.[6]
- *Short-run adaptation*, which involves using only variable inputs to adapt to climate change, vs. *Long-run adaptation*, which involves adjusting both variable and fixed factors (land and capital) to adapt to climate change and, perhaps even more importantly, by changes in the production technology itself.

All of these definitions are generally worth thinking about, and while most of them contain elements that can be useful in economics, some are too general, or wrong-headed, to be considered an economic definition, and a few are incoherent, at least in terms that economists would understand. For example, the distinction between autonomous and planned adaptation has been, and continues to be, widely used (Smit et al., 2000). The idea that autonomous adaptations are "spontaneous" responses by "systems" to climate change and variability makes a good deal of sense in the context of unmanaged ecosystems where plants and other living organisms are concerned. At the same time, its counterpoint, planned adaptation, can be stretched a bit to apply to managed ecosystems. However, in terms of economic systems this distinction becomes far less meaningful if one considers that, except for coping with sudden extreme events at the moment they occur, humans are often assumed to have both economic and non-economic objectives that they optimize, subject to both economic and non-economic constraints. In other words, planning takes place. Recognizing this, the term is more generally, and loosely, used by economists to reflect changes in resource allocation decisions (planned in the short- and long-run) at the individual, household, and firm levels due to the direct shocks of climate change on managed and unmanaged ecosystems and the indirect effects that occur as a result of these decisions on market prices throughout the economy as a whole. However, the question arises of where this leaves autonomous adaptation if almost all adaptation is planned,[7] at least in terms of rational decision-making processes.

One answer is given by Füssel (2007), who argues that planned adaptation to climate change "means the use of information about present and future climate change to review the suitability of current and planned practices, policies, and infrastructure". He then goes on to define planned climate change adaptation strictly in terms of conducting formal assessments prior to taking action. This definition could well fit an engineering and economic analysis of an infrastructure project, like a water supply or flood control reservoir, but wouldn't necessarily preclude the "autonomous" actions of a farmer who is deciding what crops to plant, given that the farmer is using the best available information from all sources about the effect of climate change on growing season weather to make planting decisions. What actually differs is the type of project (a long-run investment vs. a short-run management decision) and how and for what purpose the planning is done. Thus, the line between this distinction – autonomous vs. planned adaptation – is far too fuzzy to be useful as an economic point of reference, essentially in the case of economic systems.

This takes us to the distinction between private- and public-sector adaptation, a descriptively useful distinction based on who adapts to climate change. As such, autonomous adaptation would be the sole domain of the private sector and planned adaptation the sole domain of the public sector. However, this is a very narrow way of describing what adaptation is, since both groups must plan (act rationally) to adapt

6 There is no opposing term to no-regrets adaptation, unless it be "maladaptation", which is an incongruous concept from the standpoint of economics.

7 The alternative to planned (rational) behavior is "irrational" or random behavior (Silberberg, 1978).

to climate change, although usually, but not always, they do so with different objectives and constraints. Thus, while this distinction has considerable descriptive value, it is not by and large useful in defining adaptation from an economic point of view.

The distinction between anticipatory (sometimes referred to as "proactive") adaptation and reactive adaptation makes as little sense to an economist as the distinction between autonomous and planned adaptation. This is because the distinction is not only more normative than analytical in tone, but also because the timing of an adaptation response lies within the realm of economic decision-making. In an economic framework, it makes little sense to take an action to adapt to climate change today, rather than tomorrow, if the expected net benefits of waiting until tomorrow are greater than those of taking the action today. Moreover, from a Bayesian perspective, the act of waiting for better information to avoid economic losses based on today's "bad" information pays dividends in and of itself. Thus, while this distinction can be bent in certain ways to conform to economic theory, it is cast in such a way as not be useful in defining adaptation in economic terms.

No-regrets adaptation refers to actions that are undertaken for objectives other than adapting to climate change, but that will nevertheless result in positive net benefits if the climate does change.[8] A good example would be a change in water allocation laws that would allow different users in a water market to compete for water, rather than by allocating water to different users by means of quotas. In both theory and practice, the use of market mechanisms results in a more economically efficient allocation of water, as well as increased flexibility to respond to climate variability and greater incentives to conserve water. As Callaway et al. (2008, 2009) have shown in the Berg River Basin, Western Cape, South Africa, such an approach would substantially increase the net benefits to water users in the basin and, under climate change conditions, make it virtually unnecessary to build a large storage reservoir as a buffer against climate change. Thus, this concept is useful when casting adaptation in an economic framework.

The final distinction, between short- and long-run adaptation, is an economic construct that we find very useful in describing how economic agents adjust to climate variability and change. In the short-run, adaptation involves the use of resources that are already available for use, such as labor and energy and other variable inputs. However, their use in adapting to climate change is constrained by the presence of fixed resources, such as land and capital. In the long-run, both types of resources are available for adaptation, creating situations in which the long-run response will yield greater net benefits than the short-run response. The importance of this distinction to the economics of adaptation will be further developed and illustrated in a later section of this chapter.

Leaving aside the different types of adaptation, let us re-focus for the moment on the existing definitions of adaptation to climate change.

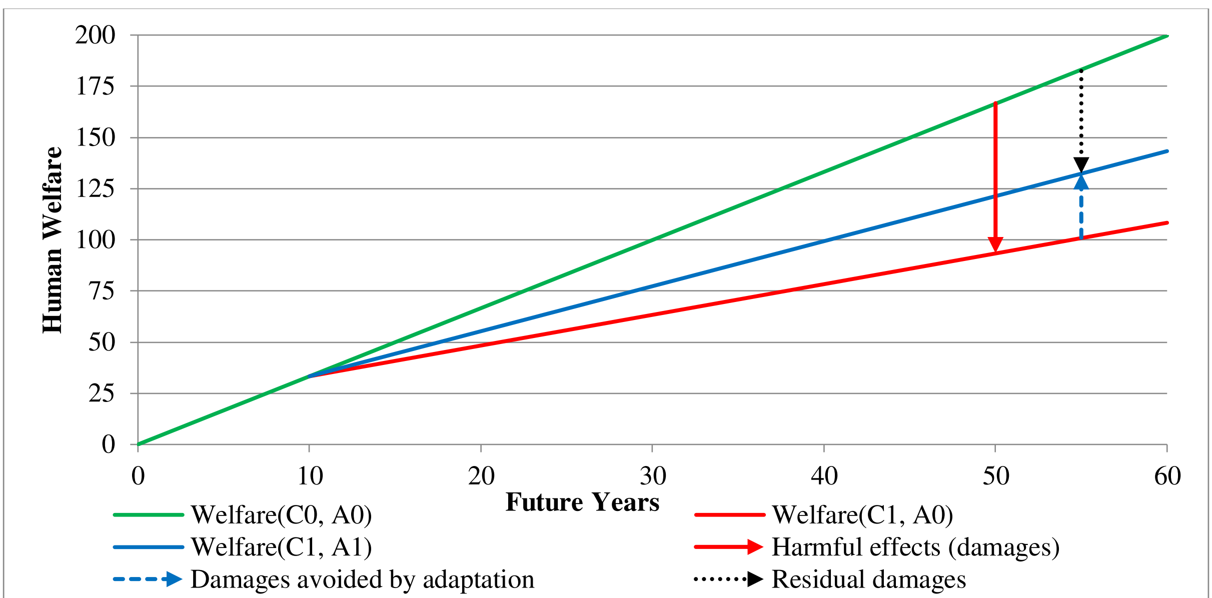
All three definitions (IPCC, EC, and UNDP) suggest that the effects of climate change have the potential to be harmful or beneficial to humankind, and that adaptation represents a response to avoid the harmful effects or to take advantage of the beneficial effects. This is illustrated in Figure 2.1 for the harmful effects and, later on, in Figure 2.2 for the beneficial effects.

8 The concept of economic regrets can also apply to situations involving risk and uncertainty when one plans and builds, say, a flood control reservoir for a future climate "C1" in which runoff is highly variable, but a very dry climate "C2" is what actually happens and the reservoir is not needed at all. Strictly speaking, a no regrets result in this case would result in a reservoir design, or other measures, that performs almost equally well under both climates.

The Y-axis in both figures measures "human welfare" – a perfectly general term, the only requirement for which is that this measure has continuous values that are comparable over the different time periods on the X axis.[9] The green, blue, and red lines represent the evolution of human welfare over time under three different welfare scenarios that are relevant for measuring the benefits and costs of adaptation. All of them are linear, except for the break at year 10, when climate change is assumed to occur. The welfare scenarios are defined as follows:

- Welfare (C0, A0), shown by the green line, which is influenced by the existing climate (C0) and the existing technology (A0) used to adapt to climate variability under the existing climate. This is the Base Case scenario in which no climate change occurs.
- Welfare (C1, A0), as shown by the red line, which is influenced by climate change (C1) and by the existing technology (A0) that is used to adapt to climate variability under the existing climate. This is the Climate Change Damage scenario, in which the climate changes, but the suite of adaptation technologies used to adapt to climate variability (and not climate change) does not change. This is sometimes referred to, conceptually, as the "no adaptation"[10] scenario.
- Welfare (C1, A1), as shown by the blue line, which captures the situation when there is a specific adjustment to climate change (C1) through the adoption of new technology and behavior (A1) to adapt to climate change and its variability. This is the Adaptation Scenario, in which these adjustments reduce climate change damages. It is also possible that the existing technology can be used to cope with climate change by short- and long-run adjustments of existing variable inputs and the capital stock. This will be investigated in a later section dealing with short- and long-run adaptation.

Figure 2.1. Illustration of Adaptation to Harmful Effects of Climate Change.



9 This is used to measure and compare, on a cardinal scale, the "value" of undertaking adaptation measures and is only used for conceptual purposes.

10 The idea of a "no adaptation" scenario is not terribly realistic under an economic definition, unless there is absolutely no information available to detect climate change. The "no adaptation" case is used, here, strictly as a conceptual reference. Later on in this chapter a close substitute for the "no adaptation case" will be presented, the "pure effect" of climate change.

In Figure 2.1, human welfare is shown to evolve over time under the existing climate (C0) and existing means of adapting to existing climate variability (A0) by the green time path of welfare. This is both a projection and a counter-factual "Base Case", if as can be seen, the climate is expected to change in a harmful way. Under the adverse climate damage scenario, welfare decreases as shown by the red downward facing arrow between this scenario and the Base Case. The decrease in welfare is due to both the effects of the adverse climate and the fact that the Base Case suites of practices and technology (A0) s not perfectly suited, along this welfare path, to cope with the climate change (C1). This welfare path always lies below the Base Case welfare path in Figure 2.1, indicating decreased human welfare after year 10. Thus, the harmful effects (damages) of climate change can be measured at any point in time by the welfare decrease between the two paths, Welfare (C1, A0) - Welfare (C0, A0) < 0. This difference is illustrated by the red arrow between these two welfare paths. This case of limited adjustment to climate change can be factual and observable, because humans are adjusting to climate change as if were climate variability under the existing climate; or it can be counter-factual, if and when humans do start adapting to climate change.

Under conventional definitions, adaptation to adverse climate change involves adjustments by humankind to reduce the harmful effects specifically of climate change. The effects of these adjustments on human welfare are illustrated by the blue time path that reflects both climate change (C1) and, now, human adjustments to reduce the harmful effects specifically due to climate change, including its variability (A1). This adaptation welfare path always lies above the climate damage welfare path, indicating that some of the damages due to climate change have been avoided by adaptation. The net welfare benefits of avoiding these damages by adaptation to climate change are illustrated by the dashed, upward facing blue arrow between the two paths, or Welfare (C1, A1) - Welfare (C1, A0) > 0.

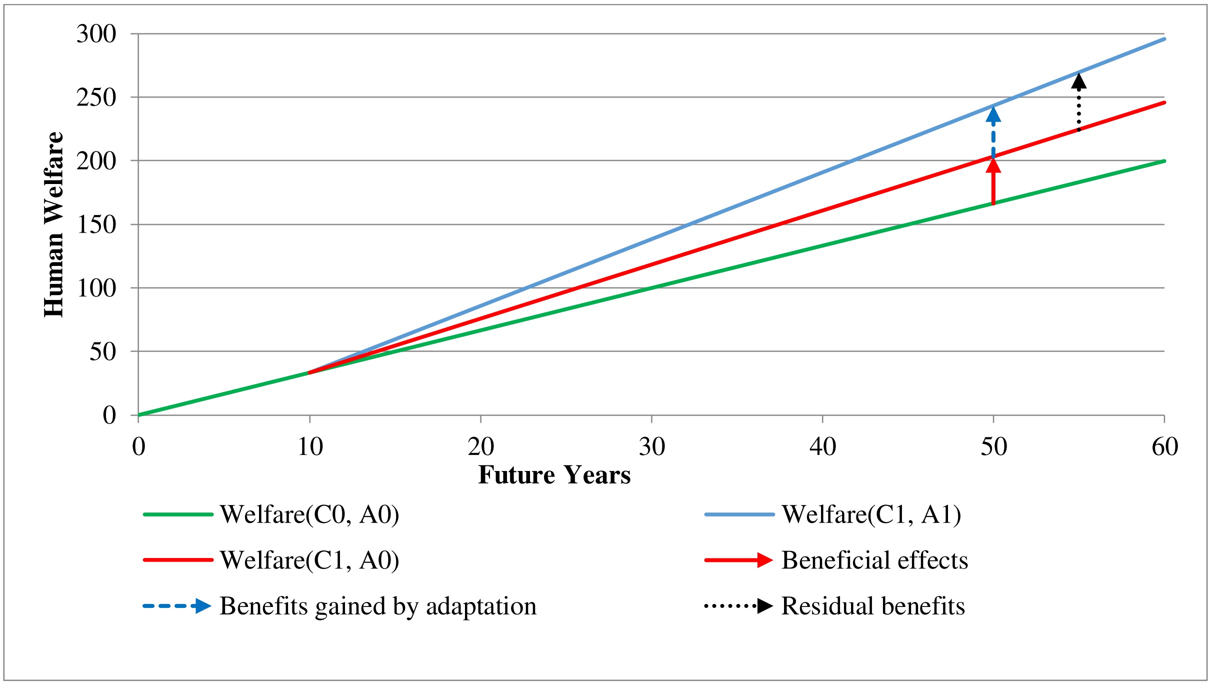
However, adaptation to climate change, as portrayed in Figure 2.1, does not avoid all of the damages caused by climate change, because either some physical damage is technologically irreversible, or else it is too costly to avoid additional damages. The damage left is known as the residual climate change damages, shown by dotted black arrow that lies between the Base Case welfare path and the adaptation welfare path. This welfare difference is measured by Welfare (C1, A1) - Welfare (C0, A0)[11] ≤ 0.

Figure 2.2 illustrates a case where climate change has beneficial effects in some places and sectors, for example, due to CO_2 fertilization of crops, or the beneficial effects of warmer weather in northern latitudes on tourism, energy demand, and agriculture. However, beneficial effects are far less likely in developing countries that lie closer to the equator.

Except for the fact that climate change has beneficial effects, the same general concepts apply to this illustration as to Figure 2.1. Climate change increases welfare, so the climate damage welfare path, Welfare (C1, A0), lies above the Base Case welfare path, Welfare (C0, A0), even with incomplete adjustment. Thus, the beneficial effects of climate change can be measured at any point in time by the welfare decrease between the two paths, Welfare (C0, A0) - Welfare (C1, A0) > 0. However, humans can adjust more fully to climate change and these actions lead to even higher welfare path, Welfare (C1, A1). In that case, Welfare (C1, A1) - Welfare (C1, A0) > 0. Finally, in this case, there are no residual damages, only residual benefits, since the adaptation welfare path lies above the Base Case welfare path. So, in this case Welfare (C1, A1) - Welfare (C0, A0) > 0.

11 There can be cases where the welfare gains of adapting to climate change are greater than the welfare losses due to climate change, in which case there is no residual damage.

Figure 2.2. Illustration of Adaptation to the Beneficial Effects of Climate Change.



An Economic Definition of Adaptation

Figures 2.1 and 2.2 are both consistent with conventional "official" definitions of adaptation, which are very general and universally accepted, being generated by public policy processes that strive to be transparent and inclusive. Nevertheless, as these definitions have been fine-tuned over time, they have become increasingly "better" for just these reasons. What all of them share in common are the ideas that:

- Human welfare is influenced by the effects of climate change.
- The impacts of climate change on welfare can be positive or negative.
- By adapting to the effects of climate change, human welfare will be improved relative to the Base Case.

However, while the concepts in these definitions do apply broadly to the economics of adaptation, they do not go far enough to explain how and why humans may respond to climate change and how the various welfare adjustments are measured. Let us start with an economic definition of adaptation and then show what it implies about the nature of decision-making and behavior in general and, more narrowly, what it implies about the scope and types of adaptation that are consistent with the definition.

Adaptation to climate change consists of the adjustments in resource allocation that economic agents[12] *make in their consumption, production, and investment decisions to avoid the economic losses, or to increase the economic gains, due directly or indirectly to the effects of climate change.*

12 Economic agents refers broadly to individuals, households and "organizations" involved in the production, consumption of and investment in goods and services.

The first thing to notice about this definition is that it is consistent with the three main ideas that the conventional definitions share in common. However, the definition removes "adjustments in natural systems" (IPCC) from the scope of the adaptation. This is simply because adjustments in natural systems to climate change are a part of the exogenous effects of climate change to which economic agents, in turn, adjust. That limits the scope of adaptation to "economic agents", which is sufficiently broad to involve every person and organization, whether as a buyer, seller or investor with links, however weak, to formal or informal markets. However, most importantly, it specifically defines adaptation actions generally as "adjustments in resource allocation" that are driven by economic incentives to improve, specifically, economic welfare. While this definition has a market-oriented ring around it, it does not in fact limit the scope of adaptation to market activities and market goods and services. To use an example from forestry economics, adaptation not only includes adjustments by economic agents who are involved in the production and consumption of primary and secondary forest products that are bought and sold in markets, but also backpackers, hikers, berry-pickers and other recreational "users" of forests. What this definition does exclude are the impacts of climate change on human activities that do not involve a re-allocation of real resources as a part of the adaptation adjustment. This excludes the realm of non-use values, such as existence values, which rely heavily on the stated preferences of individuals as revealed through surveys and interviews instead of revealed preferences based on observation of how economic agents behave (Cummings et al., 1986; Desvousges et al., 1983; Krutilla, 1967; Krutilla & Fisher, 1975; Mitchell & Carson, 1981; Randall & Stoll, 1983).

Money Metrics for Adaptation

The economic definition of adaptation supplied above is based on the use of money metrics to measure changes in human welfare and an underlying theory about how individual economics allocate resources to consumption, production and investment in response to exogenous changes in the environment. It is a common practice to discuss theory first and metrics second. However, the specific metrics will be discussed first because they are directly related to the information presented in Figures 2.1 and 2.2 and, hopefully, are still fresh in the reader's mind. More importantly, the decision to monetize some impacts and the benefits and costs of some adaptation measures does not have to be based on economic theory of how individual economic agents and markets behave. These same metrics can be used simply as accounting tools.

So, looking back at these two figures, the following economic metrics have been developed (Callaway, 2003; Callaway, 2004; Callaway et al., 1999; Fankhauser, 1997) to capture the benefits and costs of adverse climate change:[13]

- Climate Change Damages: the change in net economic welfare that occurs *relative to the Base Case Scenario,* W(C0, A0), when climate changes but economic agents adapt to it, using only the resources and technologies available to them to adjust to the existing climate variability in the Base Case (A0).
- Adaptation Benefits (not shown): the change in welfare benefits that occurs, *relative to the Climate Change Damage Scenario*, W(C1, A0), when economic agents adjust to climate change by changing their resource mix and switching to technologies to cope better specifically with climate change and its variability (A1).

13 Long-run adaptation can, and may frequently, involve increasing capital stocks of the technologies used to cope with existing climate variability, which should often be the case if the technology is robust enough to function well under existing climate variability and climate change.

- Adaptation Costs (not shown): the change in the real costs of adapting to climate change, *relative to the Climate Damage Scenario*, by implementing these adaptation technologies (A1).
- Net Benefits of Adaptation: the difference between Adaptation Benefits and Adaptation Costs.
- Residual Damages/Benefits: the difference between Climate Change Damages and the Net Benefits of Adaptation. If the Net Benefits of Adaptation are greater than the Climate Change Damages, the residual is a benefit, not a cost.

From a conceptual standpoint (once the measure of net economic welfare is selected), these metrics are calculated as shown in Table 2.1, which we can see are conceptually based on Figures 2.1 and 2.2.

Table 2.1. Definitions.

Metric	Calculation of Metric as Illustrated in Figures 2.1 and 2.2
Climate Change Damages	W(C1, A0) - W(C0, A0) < 0 for damaging climate change
Net Benefits of Adaptation	W(C1, A1) - W(C1, A0) > 0 for adaptation improvements
Residual Damages	W(C1, A1) - W(C0, A0) < 0 if the Net Benefits of Adaptation are less than Climate Change Damages in absolute terms
Residual Benefits	W(C1, A1) - W(C0, A0) >0 if the Net Benefits of Adaptation are greater in absolute terms than Climate Change Damages

All definitions are according to Callaway (2003)

Private or Social Benefits and Costs

In continuation with the above metrics, a key determination to be made in an adaptation assessment is constituents of costs and benefits. These constituents will be different while estimating costs and benefits using a private perspective as opposed to a social perspective thereby influencing the overall estimation of adaptation metrics discussed above. The private market perspective treats damages due to climate change and the benefits and costs of adaptation based on actual financial flows (or imputed shadow prices based on actual financial flows). It assumes that economic agents are maximizing their own net welfare (or minimizing their own costs) without any regard to how their allocation decisions may affect other economic agents, whether positively or negatively. The social perspective, on the other hand, is based on wider view and takes into account these external impacts. The former is appropriate if we are only concerned about the inbuilt economic incentives that economic agents have to commit resources to adapt to climate change. If all markets were perfectly competitive and free from all distortions that commonly drive a wedge between social cost-benefit and private cost-benefit accounting, the resulting benefits and costs of adaptation would be the same. However, if this is not the case *and*, for whatever reason, one wants to take into account these market failures, one would have to adjust the financial benefits and costs of adaptation from a social perspective. To do this properly constitutes an important focal point of modern economics, and the methods for estimating social values are very diverse. These aspects are not covered comprehensively in this report. However, there is, for example, extensive literature about how this has been done to estimate the social cost of carbon[14] with reference to the impact of environmental and health externalities on electricity prices in the EU and the State of New York (EC, 1995; Rowe et al., 1995), which the reader can consult.

14 There is a vast literature on this topic. Three examples to support and improve upon estimates of the social cost of carbon in the US for regulatory purposes are: IWGSCC-USGOV (2010 and 2013) and Pizer et al. (2014).

To understand the difference in these two perspectives, let us take an example. Suppose that there are two firms (1 and 2) on a stream, one downstream of the other, who divert water from the stream, all of which they use consumptively (i.e., no return flows) to produce goods for sale in competitive markets. If the water was sold in a competitive market, then it would be easy to figure out that the economically optimal allocation between the two firms would be one for which the marginal value products (MVP is the additional profit earned from the last cubic meter of water diverted) would be equal.[15] That allocation could be achieved in a number of different institutional ways, but no matter what the allocation mechanism was, maximizing social welfare and private welfare would yield the same allocation. Now, let us assume that climate change reduces stream flow and that the upstream firm decides to use a technology to adapt to climate change that has the same water "requirements" as the one that was used before the climate changed; however, the new technology has the effect of returning some of the used water to the stream. In that case, as Hartman & Seastone (1970) have shown, the "return flow" from the upstream user introduces a positive technological externality into the allocation decision. The private decision rule, which equalizes the marginal value product of the two water-users, is no longer socially optimal because the downstream water-user would now have access to the upstream user's return flow. In that case, a social optimum would be achieved when the marginal value product of upstream consumptive use plus the marginal value product of return flow use downstream equaled the marginal value product of downstream consumptive use.[16] In fact, both the private and social equilibriums are stable and could probably be achieved amongst a small number of users, where transactions costs for information would be low. In that case, if the social allocation was actually observed, it would be appropriate to compute adaptation benefits and costs from the social perspective, even if a competitive market could achieve the same result by externalizing the externality (Callaway, 1979; Hartman & Seastone, 1970).

A Theory of Economic Adjustment Applied to Adaptation

To our knowledge, the relationship between short- and long-run adjustments to climate change (not increased demand) has not been investigated formally, and the growing body of applied literature on impacts and adaptation often fails to make a clear distinction between short- and long-run measures, or of the relationship between them.

In the section on 'official definitions of adaptation', it was pointed out that some of the different types of adaptation definitions that have been used in the literature did not make a great deal of sense from an economic perspective. In this section, the distinction between short- and long-run adaptation is explored in depth to show its relevance for explaining not only how economic agents may actually adjust to climate change, but also the importance of differentiating the adaptation benefits and costs between adaptation actions that involve capital investments and those that involve changing variable inputs.

The general economic theory that underlies adjustment by economic agents to climate change is not new and can be applied broadly to the effects of almost any kind of exogenous change in the environment on resource allocation by economic agents in their various capacities. Here we will approach this topic from the standpoint of production theory, covering not only the production of market goods, but also household and non-market goods whose supply and/or demand is influenced by changes in the environment, directly or indirectly due to climate change.

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15 $MVP_1 = MVP_2$, where MVP is the marginal value product of stream water.

16 $MVP_1 + r_1 * MVP_2 = MVP_2$, where r_1 is the fraction of water used by the first farm that is return flow.

Underlying production theory is the concept of the production function that translates inputs in the production process into outputs. In a climate change framework, the inputs can be boiled down into three[17] main types:

- Variable inputs (x) that can be changed in both the short- and long-run, such as labor, energy, irrigation water, many material inputs, etc.
- Fixed inputs (k) that cannot be changed in the short-run, but become variable in the long-run, such as land, built infrastructure, large machines, etc., all of which are sometimes lumped under the heading of capital.
- Climatic inputs (c), such as temperature, precipitation, and wind that can have harmful or beneficial effects, directly on production, or indirectly through the effects of climate on the environment.

For the moment, this chapter will focus on the effects of climate change on production and the subsequent adjustments made by economic agents along their short- and long-run supply and demand curves to adapt to climate change. Both types of supply functions are based on the idea that producers want, among other things, to find the least cost solution for producing given levels of output in the short- and long-run. If the production function is Q=f(x, k, c), the total cost and supply functions/curves can be represented as follows:

Minimize long-run total cost (LRTC) = $r_x x + r_k k | Q\text{-}f(x, k, \mathbf{c})$: LRTC(Q, r_x, r_k, **c**) ***Equation 2.1***

Minimize short-run total cost (SRTC) = $r_x + r_k \mathbf{k}$ |Q-f(x, **k**, **c**) :SRVC(Q, r_x, r_k, **c**) + $r_k \mathbf{k}$ ***Equation 2.2***

where r_x and r_k are, respectively, the exogenous unit prices of labor and capital, SRVC is the short-run variable cost, the bold **k** and **c** indicate that capital is fixed and climate, which is not under the control of producers and consumers, and SRVC( ) is the short run variable cost function.

The long- and short-run marginal cost (Supply) functions/curves are derived by taking the first derivatives of the LRTC and SRVC functions with respect to Q:

Long-run marginal cost (LR-Supply) = $\frac{\partial LRTC}{\partial Q}$ = LR-Supply (Q, $r_{x,}$ r_k, **c**) ***Equation 2.3***

Short-run marginal cost (SR-Supply) = $\frac{\partial SRVC}{\partial Q}$ = SR-Supply (Q, $r_{x,}$ r_k, **k**, **c**) ***Equation 2.4***

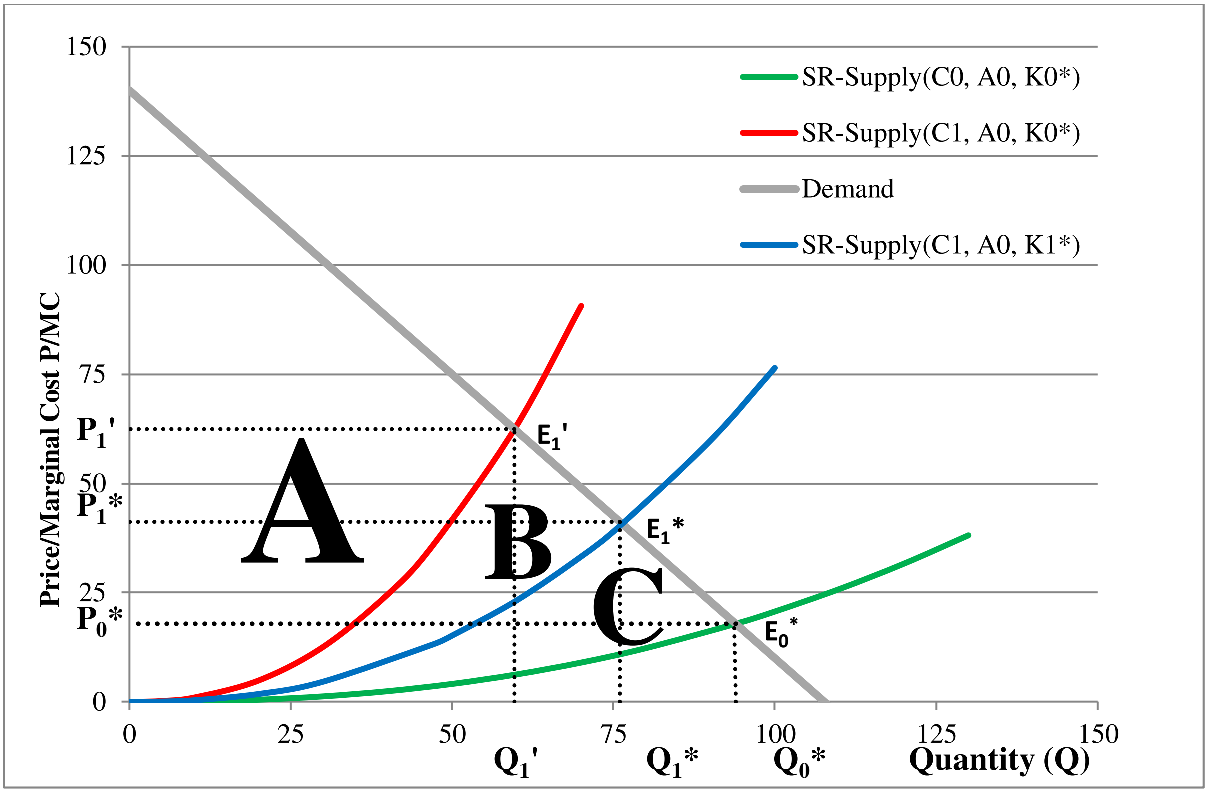
Short-run Adaptation

Figure 2.3 illustrates the role by played by short-run supply curves (only) in adjusting to climate change when economic agents adjust only the capital stock, *without (K) changing technology (A) as defined by the structure of their production function and its parameters*. It does not show the underlying long-run supply curves, which will be presented in a later discussion. It is presented in the context of an example involving the production and consumption of a market good in the short run, where land and capital are fixed, and only variable inputs, such as planting and harvest dates, labor and fertilizer, can be varied initially in response to climate change. Then, to adjust more fully, economic agents are able to adjust merely their variable inputs and capital stocks. This figure is based on both comparative static and applied

17 Climatic and environmental inputs are treated as a single type of input in so far we are only concerned with the direct effects of climate and climatically induced changes in the environment, with climate being the independent variable in both cases.

analysis (Callaway, 2014; Callaway et al., 2008 and 2009). To make it easier to follow, an example from an agricultural production market for maize is used.

Figure 2.3.[18] Illustration of the Role of Short-run Supply Curves tin Adjusting to Adverse Climate Change in a Product Market.



The Marshallian aggregate demand curve for the product, for example maize, is illustrated in Figure 2.3 by the downward sloping grey line, which, for the sake of simplicity, is not affected by climate change. The demand curve is a trace of the marginal willingness to pay of consumers in the market (on the vertical axis) for a given quantity of maize consumption (on the horizontal axis). The figure also includes three short-run supply curves, each of which reflect one of the scenario time paths illustrated in Figures 2.1 and 2.2 using essentially the same functional notation (and colors) as in these figures. Each of these supply curves is based on Eq. 2.2 and each is a trace of the minimum marginal variable cost[19] of producers in the market (on the vertical axis) for a given quantity of maize output (on the horizontal axis), holding the capital stock constant. However, as indicated above, it is assumed that all of the supply curves are characterized by the existing technology (A0), which denotes that the type and parameters of the production function (i.e., technology) are optimal for adjusting to existing climate variability, not necessarily climate change. What

18 The supply and demand curves in Figure 2.3 and in the figures after it in this chapter were simulated using total cost and supply (marginal cost) functions derived from the Cobb Douglas production function (Cobb & Douglas, 1928). The equilibrium conditions were determined by finding the demand price that equaled the marginal cost of production along each supply curve.

19 The fact that these are marginal *variable* cost curves means that the area under them does not include total fixed costs (see Eq. 2.2). Furthermore, SRTC equals LRTC only where the long- and short-run supply curves intersect one another.

varies is the capital stock, holding technology constant. The short-run supply function for the Base Case, SR-Supply(C0, A0, K0*), denotes that the level of the capital stock (K0*) is optimal (least cost) from the standpoint of climate, supply and demand. For SR-Supply (C1, A0, K0*) in the climate damage case, the technology (A0) does not change, nor does the capital stock: it is still fixed at its original level, K0*. As a result, the supply function is not optimal from the standpoint of climate. The optimal adjustment of the capital stock (only) is reflected in the short-run supply curve, SR-Supply(C1, A0, K1*), given that the technology remains at A0.

For each supply curve, there is competitive market equilibrium between supply and demand where the marginal short-run cost producers along the supply curve equals the marginal willingness-to-pay of consumers along the demand curve. This competitive market equilibrium in each of the three cases determines the market price (P) and the quantity (Q) of maize that is produced. The bold letters A, B, C have been inserted for welfare accounting purposes and will be discussed shortly.

The initial market equilibrium under the existing climate (C0) using conventional technology of adapting to existing climate variability (A0), with the optimal capital stock K0* (consistent with both C0 and A0), is characterized by the market equilibrium E_0*, for which the output quantity in the market is Q_0*, and the market price is P_0*. This market equilibria, as well as the others shown in this figure, are consistent with producers in the market setting their marginal cost of production along their short-run supply curves – in this case the SR-Supply(C0, A0, K0*) curve – equal to the market price they face as price-takers. This is the status quo.

The assumption in this example is that adverse climate change reduces maize yields due to drier conditions. This has the effect of shifting the short-run supply curve, SR-Supply(C0, A0, K0*), to the left (Callaway, 2014) so that it effectively becomes the supply curve, SR-Supply(C1, A0, K0*), with the same fixed factor quantities of capital in both functions. However, when the climate changes, farmers in the market are still able to adjust their variable inputs, a partial response. For example, farmers can adjust planting dates, change their crop mix, or in some case alter tillage practices. The short-run climate damage supply curve associated with this partial response always lies above the Base Case supply curve, meaning that each output level on the horizontal axis costs more to produce in terms of marginal costs than in the Base Case. The short-run market equilibrium, E_1’, associated with the adverse effects of climate change, results in a decrease in maize production from Q_0* to Q_1’ and an increase in maize price from P_0* to P_1’. However, as was implied in Figure 2.1, maize producers have further short-run economic incentives to change variable inputs and, now, the capital stock, which are not optimal for the change in climate. For example, farmers may require new types of tractors (or draught animals) and plows to undertake some soil tillage practices. These new production opportunities are reflected in the short-run supply curve, SR-Supply(C1, A0, K1*), along which output can be increased at lower marginal costs. In other words, producers can adapt more fully to climate change than was possible along SR-Supply(C1, A0, K0*). The resulting equilibrium, E_1*, is characterized by the market output maize quantity Q_1* and the maize price, P_1*. As this result is static, further adjustments over time similar to those depicted in Figure 2.1 can be expected to occur.

Welfare Accounting

The welfare accounting for this example and all others in this report is based on the concepts of consumer and producer surplus (Silberberg, 1978). Short- and long-run welfare accounting follow the same general principles. However, short-run supply curves do not take into account the costs of investing in capital stocks.

- *Consumer surplus* is the difference between the maximum amount of money a consumer in a market is willing to pay for a good or service and the amount of money paid for the good or service, rather than not consume it. This is an approximate measure of the net welfare benefit of buying and consuming the good or service.
- *Producer surplus* is the difference between the amount that a producer of a good or service receives and the minimum amount that the producer would be willing to accept for the good, rather than not produce it.
- *Total Surplus (Net Benefits)* is the sum of producer and consumer surplus.

Consumer surplus associated with the consumption of a good is measured geometrically by the area under the Marshallian demand curve (D) for a good, down to the price of the good. This is shown in Box 2.1 by the triangular area labelled "Consumer Surplus". The equivalent type of measurement for producer surplus is the area above the supply curve (S), up to the market price of a good, as illustrated in Box 2.1 by the triangular area, labelled "Producer Surplus". In a market context, these surpluses can be aggregated over all consumers and producers in the market ,and the sum of the two is an approximate welfare measure of the net welfare benefits.

An alternative way to calculate the sum of consumer and producer surplus is by subtracting consumers' willingness-to-pay (WTP) for a good less the cost of the good. WTP can be measured by the total amount of money a consumer is willing to pay for a good, rather than do without it. It is measured geometrically by the area underneath the Marshallian demand curve from the origin to the quantity consumed. In figure 2.4, this includes the sum of the areas labelled Consumer Surplus, Producer Surplus, and Cost. To arrive at the sum of producer and consumer surplus, one simply deducts the cost.

Figure 2.4. Consumer and Producer Surplus.

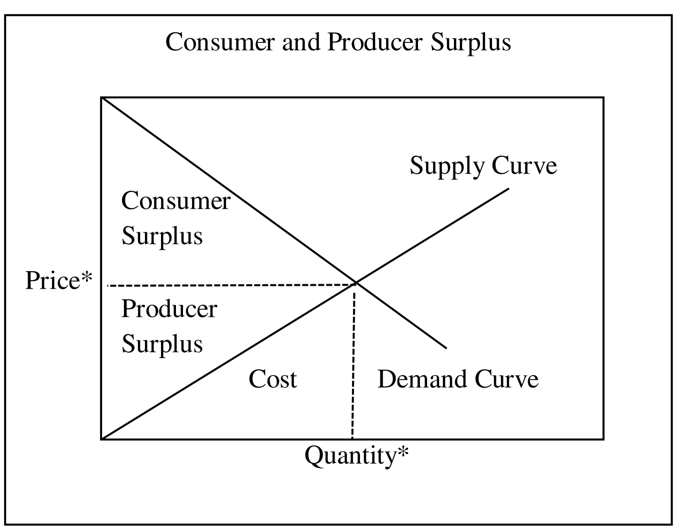
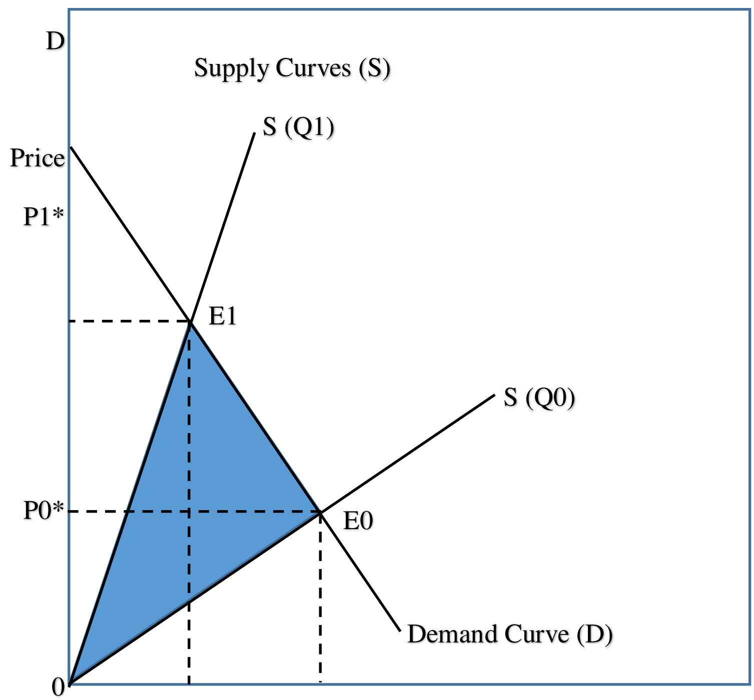


Figure 2.5 shows how a shift in the supply curve to the left, from S0 to S1, reflecting an effect of adverse climate change, affects the sum of producer surplus and consumer surplus. When the supply curve shifts from S0 to S1, the price-quantity equilibrium shifts from E0(P0, Q0) to E1(P1, Q1), and the decrease in total surplus can be measured geometrically by the transparent, blue-shaded area, 0E1E0, between the two supply curves. This includes the change in both the consumer and producer surpluses combined. The only difference in the computation of this total welfare change between the short- and long-run is that the short-run welfare loss includes only the changes in variable costs, while the long-run welfare loss includes both variable and capital costs. The relationship between short- and long-run supply curves is addressed in figures 2.6–2.8.

Finally, the principles of welfare measurement discussed in this and Box 2.1 can also be applied to input and factor markets of all kinds. The only difference, conceptually, is that the demand curve represents the derived demand of producers for the input and the supply curve measures the marginal cost curve for the input or factor.

Figure 2.5. Effect of Climate Change on the Sum of Producer and Consumer Surplus.



Following the illustrated definitions in the two text boxes, the short-run total surplus (net benefits to consumers and producers) associated with the Base Case market equilibrium for maize (C0, A0) is measured in Figure 2.3 by the pie-shaped area that is the sum of the area A and areas between the two supply curves, B+C, in other words by the area, A+B+C. From this starting point, the metrics defined algebraically in Table 2.1 can be used to match the changes in net welfare illustrated in Figure 2.3. First of all, the effects of climate change alone due to the shift in supply curves from SR-Supply(C0, A0) to SR-Supply(C0, A1) causes a loss in short-run total surplus equal to the negative sum of the geometric areas, - (B+C). This area represents the short-run climate change damages. Next, short-run adaptation, as reflected by the shift in the short-run supply curves, from SR-Supply(C1, A0) to SR-Supply(C1, A1), causes an increase short-run total surplus equal to the geometric areas, B. This area represents the net benefits of short-run adaptation. This leaves the geometric area, -C, a welfare loss, which represents the residual damages of climate change after adaptation has taken place. To summarize:

- *Short-run Climate change damages:* Net Benefits(C1, A0, K0*) - Net Benefits(C0, A0, K0*) = - (B + C) < 0,
- Short-run Net benefits of adaptation: Net Benefits(C1, A0, K1*) - Net Benefits(C1, A0, K0*)= + B > 0, and
- *Short-run Residual damages:* Net Benefits(C1, A0, K1*) - Net Benefits(C0, A0, K0*) = - B < 0.

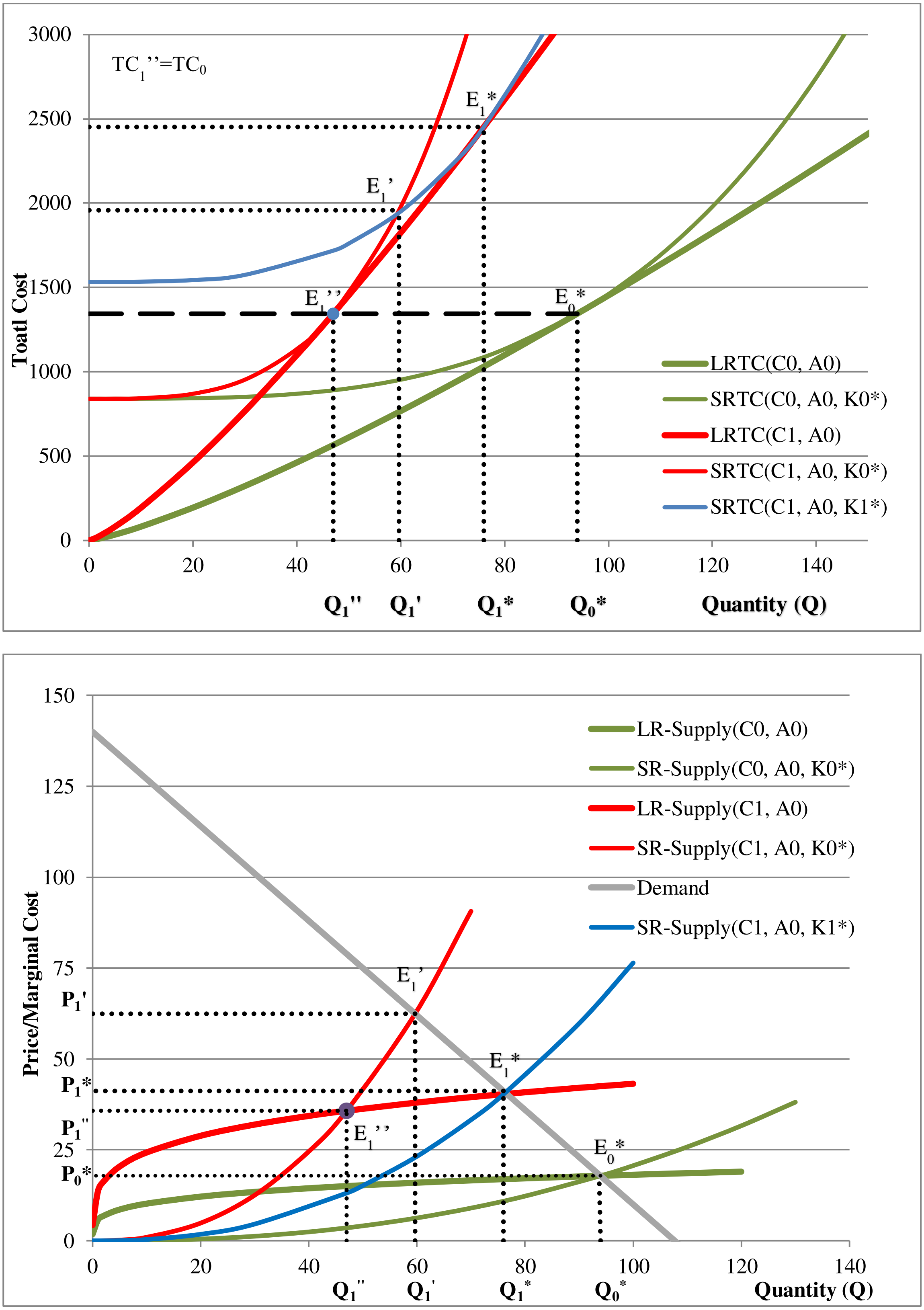
The Bigger Picture: The Relationship between Short- and Long-run Adaptation

Figure 2.3 is not the whole story because it does not include the important relationship between short- and long-run adjustments to climate change, nor does it include welfare accounting from the long-run perspective, compared to the short-run. Finally, it does not account for changes in technology, as defined by changes in the type and parameters of the production function. Figures 2.6 and 2.7 take one step forward by illustrating how economic agents (farmers) can adjust to climate change along both the long- and short-run total cost and supply functions/curves in relation to one another even when there is no change in the production technology, only in variable and fixed inputs.

The top panel of Figure 2.6 shows the long-run total cost curves for two different climate states, LRTC(C0, A0) for the Base Case and LRTC(C1, A0) for the case in which the climate changes. Each of these curves is a trace of total production costs on the vertical axis against output on the horizontal axis when all inputs are variable, both variable inputs and the capital stock, even when the technology is fixed at A0. Each point along the two long-run total cost curves reflects a total cost-minimizing mix of variable inputs (x) and capital (k), the only difference between the two LRTC curves being the effects of two different climates. Note that all of the long-run total costs on LRTC(C1, A0, K0*) are greater than those along LRTC(C0, A0, K0*) for a given level of output, Q, implying that long-run total costs are always higher along the former compared to the latter, where the capital stock is not varied to be consistent with C1.

Still in the upper panel, a single short-run total cost curve, SRTC(C0, A0, K0*), is shown*. The curve we see actually reflects just the total variable costs for each level of output, since fixed costs do not vary with output.* It is important to note, first, that SRTC(C0, A0, K0*) is tangent LRTC(C0, A0) at a single point, E_0^*, in the upper panel and this tangency is translated into the lower panel at the point, E_0^*, where SR-Supply(C0, A0, K0*) intersects with LR-Supply(C0, A0). Associated with these two points are a single level of output, Q_0^*. This requires a bit of explanation. The tangency between SRTC(C0, A0, K0*) and LRTC(C0, A0) takes place at the least cost point on SRTC(C0, A0, K0*), which is unique, given the capital stock K0*. At this point only along this short-run supply curve are short-run total costs equal to long-run total costs. This corresponds to the point in the lower panel where long- and short-run marginal costs are also equal. Therefore, any small movement away from this point in either direction along the short-run total cost curve, by changing variable inputs (holding K0* constant), will result in higher short-run total costs.

Figure 2.6. Illustration of Short-and Long-Run Adjustments to Climate Change.



Secondly, also note that the aggregate demand curve passes through the intersection of the long- and short-run supply curves in the lower panel. This means that the market equilibrium point defined by P_0* and Q_0* (E_0* in Figure 2.6) is optimal both from the standpoint of long- short-run cost minimization and for profit-maximization by producers (i.e., marginal cost = output price). This conjunction of total cost and supply and demand curves was selected based on the assumption that the market for maize is in a perfect competitive equilibrium from the perspective of supply and demand for the existing climate (C0).[20]

As previously mentioned, climate change has the effect, shown in the top panel of Figure 2.6, of shifting the long-run total cost curve from LRTC(C0, A0) to LRTC(C1, A0), where total costs are always higher for a given level of Q as compared to LRTC(C0, A0). This same phenomenon is also shown in the upper panel with respect to the short-run total cost curves, where LRTC(C0, A0, K0*) moves to become LRTC(C1, A0, K0*). It also occurs with respect to long- and short-run supply curves in the lower panel, where LR-Supply(C0, A0) shifts to become LR-Supply(C1, A0) and where SR-Supply(C0, A0, K0*) changes to SR-Supply(C1, A0, K0*). In all of these cases, the only input variables that are changed in the aggregate production function are the climate variables, and in all cases the effects of climate change increase total (and marginal) costs along the long-run and short-run total cost (and supply) functions for a given level of output. *These curve shifts are all due, solely, to cost minimization in the face of climate change.*

One phenomenon that is of interest in Figure 2.6 is the shift from the market equilibrium associated with Q_1* and P_1* in the Base Case to the point where SRTC(C1, A0, K0*) is tangent LRTC(C1, A0) in the upper panel and where SR-Supply(C1, A0, K0*) intersects LR-Supply(C1, A0) in the bottom panel at the output level of Q_1". This point is illustrated by the dots in both panels, labelled $E_1^{"}$. Looking at the top panel, we can see that the short- and long-run total costs are the same as in the Base Case, as indicated by the horizontal black dashed line that connects $E_1^{"}$ and E_0^{*}. However, the short-and long-run marginal costs, as shown the lower panel at $E_1^{"}$ and E_0^{*}, are not equal. But the point $E_1^{"}$ is not at a market equilibrium, as this point lies substantially below the demand price for Q_1", much higher on the aggregate demand curve (see E_1^{+} in Figure 2.7). Note also that, while both the long-run and total costs in the upper panel are the same at $E_1^{"}$ as for the Base Case market equilibrium E_0", output at this point is lower (Q_1" vs Q_0") and marginal costs are higher ($P_1^{"}$ vs. P_0*) in the lower panel. A question arises, namely what do we make of this situation where the short-and long-run total costs are equal and only output is reduced in response to climate change?

One suggestion (Callaway, 2014) is that the point $E_1^{"}$ represents a "pure effect" of climate change, at least for some kinds of production technology. This is because the mix of both variable inputs and the capital stock are the same at this point as in the Base Case equilibrium, and so the long- and short-run total costs are the same; however, output is much lower than in the Base Case ($Q_1^{"}$ vs Q_o*). Since the only variables that were changed in the production function in the analysis were the climate variables, this suggests that, strictly from the standpoint of supply, this point is a mirror image of the supply-side equilibrium for the Base Case, except for the climate change. Finally, no change in behavior by farmers is required to get to this point from the Base Case equilibrium, hence the term "pure effect".[21]

20 While this assumption is arbitrary, it is not without a basis in theory and is helpful for portraying the various adjustments to climate change that can take place.

21 A sufficient condition to observe the "pure effect" of climate change is the homothetic separability of the production function, which is true for the Cobb Douglas, Constant Elasticity Substitution and a number of other production functions often used in economic analysis (Griffen et al., 1987). This condition is satisfied when the dual long-run total cost function can be written as f(Q, **c**) = g(**r**).

Not to belabor the pure effect of climate change as depicted in Figure 2.6, the point E_1" is more generally instructive of a point where a farmer, or any other producer in a climate-sensitive industry, needs to decide how to change their input mix to adjust to climate change, when, for whatever reason, changing technology of the production functions (*but not the input levels*) either is not possible, too risky, or won't yield a better result. Figure 2.6 shows two alternatives, which are easiest to follow in the bottom panel.

The first is to move from point E_1" up the short-run supply curve, SR-Supply(C1, A0, K0*), to the market equilibrium point, E_1', by holding the capital stock constant and only adjusting the variable inputs until the marginal short-run cost equals the demand price at the new equilibrium price-quantity combination of P_1', Q_1'. The second alternative is to move from point E_1" along the long-run supply curve, LR-Supply(C1, A0), to the market Equilibrium point, E_1*, by changing the capital stock, for example, by purchasing land with increased soil-water retention capabilities, and by changing variable inputs that are more suited to both these soils and climate change conditions through different management practices, holding fixed capital inputs constant. The outcome of this adjustment decision is the price-quantity combination of P_1*, Q_1*. From the point E_1*, producers will then be free to adjust to climate change and/or increased demand by continuing along the new short-run supply curve, consistent with C1 and K1*, which is SR-Supply(C1, A0, K1*), or along the long-run supply curve, LR-Supply(C1, A0), in the same manner as displayed in the previous adjustments.

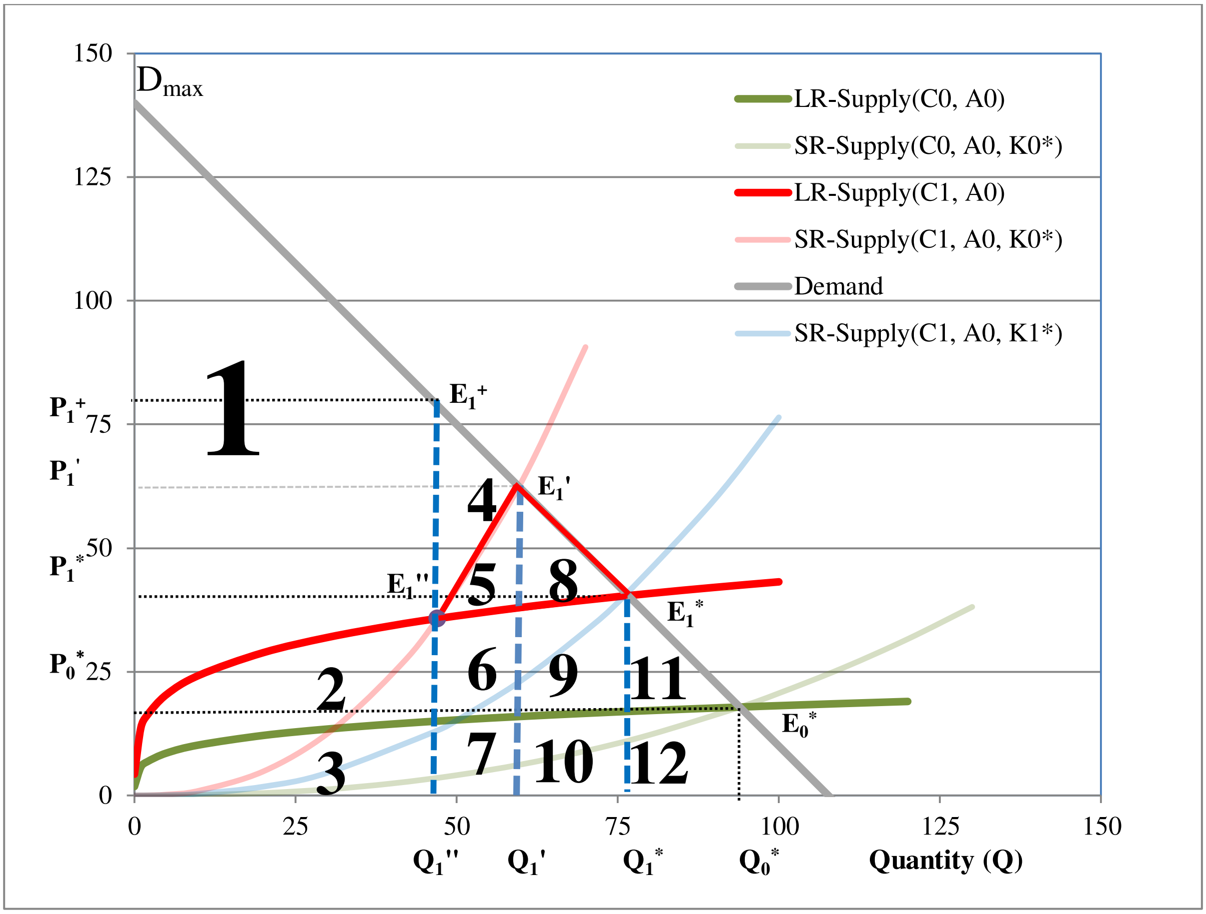
The second adjustment, involving varying both variable inputs and capital, is clearly better than the first from the standpoint of short-run welfare calculations, which only involves changing the variable inputs, as was shown in the earlier discussion of Figure 2.6. But what about the welfare calculations from a long-run perspective, as shown in Figure 2.6?

Welfare Accounting for Long- and Short-run Adaptation

The purpose of Figure 2.7 is to show how one can compute values for consumer and producer surplus for any given market equilibrium in the bottom panel of Figure 2.6 and for changes in these welfare metrics for relevant transitions between these equilibria. Ultimately, these surplus changes can be used to calculate climate change damages, both short- and long run adaptation benefits and costs and residual damages.

The only major difference between figure 2.7 and the bottom panel of Figure 2.6 is that the point E_1^+ has been added to show that the demand price at this point lies well above the supply price at E_1". This was done to illustrate that the "pure effect" of climate change puts producers in a supply position that is out of equilibrium with aggregate demand. The figure has also been divided into 1-12 discrete welfare segments, which underlie the welfare accounting principles illustrated in the two tables and their application to short-run surpluses in Figure 2.6. Numbering these areas also makes it easier to conduct a "by the numbers" approach that aligns geometric areas to welfare accounting principles. Each numbered area is bounded by either an axis and thick solid or dotted lines, or thick dotted lines. For example, the area labelled '1' is an area of consumer surplus bounded by the points $0E_1$"$E_1^+D_{max}0$, while the area labelled 10 is bounded by a thick dashed line on the left and right, the horizontal axis from below, and the thick segment of the long-run supply curve LR-Supply(C0, A0) from above. One of the problems with doing this is that the welfare meaning of each numbered area can change, depending on what is being is measured. For example, area 2 is a part of consumer surplus with reference to the equilibrium E_0*(P_0, Q_0*), but a part of the long-run cost when associated with the equilibrium at E_1*(P_1*, Q_1*).

Figure 2.7. Illustrated Welfare Accounting for Adjustments to Climate Change.



We start by evaluating climate change damages in terms of the difference in the sum of long-run consumer and surplus, first in the Base Case at $E_0^*(P_0^*, Q_0^*)$, and then at the point E_1", which defines the pure effect of climate change. All of the results in this Table 2.2 and the next Table 2.3 are based on the calculation of the sum of producer and consumer surpluses as the difference between willingness-to-pay (for maize) and the costs of producing maize. The result is included in Table 2.2.

The calculations in Table 2.2 will make more sense if they are explained in conceptual terms related to welfare accounting, starting with the Base Case. The WTP area for the calculation of CS+PS at E_0^* in the Base Case (Row 1, Col. 1) consists of the sum of all the numbered areas. This includes the area bounded by $0Q_0^*E_0^*D_{max}0$, i.e. the entire area under the demand curve and to the left of the quantity, Q_0^*. The associated long-run costs (Row 1, Col. 2) include the sum of the numbered areas under the supply curve, LR-Supply(C0, A0), and to the left of the quantity Q_0^*. The resulting sum for WTP less costs (CS+PS) for the Base Case (Row 1, Col. 3) consists of the sum of all the numbered areas above the long-run supply curve LR-Supply(C0, A0) and to the left of the quantity Q_0^*, under the aggregate demand curve.

Table 2.2. Geometric Area Calculations for Climate Change Damages between the Base Case and the Pure Effect of Climate Change.

Welfare Area	WTP Areas Column 1	Cost Area Column 2	Result: CS+PS Column 3
CS+PS at E_0* (Row 1)	1+2+3+4+5+6+7+8+9+10+11+12	-(3+7+10+12)	=1+2+4+5+6+8+9+11
CS+PS at E_1" (Row 2)	1+2+3	-(2+3)	= 1
Difference	Change in WTP	Changes in Cost	Total Difference in CS+PS
CS+PS at E_1 - CS+PS at E_0* (Row 3)	-(4+5+6+7+8+9+10+11+12)	- 2+(7+10+12)	Climate Change Damages = -(2+4+5+6+8+9+11)

Reference: Figure 2.7

The same general principles apply to the calculation of the sum of consumer and producer surpluses associated with the pure effect of climate change, for which the output quantity is Q_1”. The WTP area for the calculation of the pure effect of climate change at CS+PS at E_1” (Row 2, Col. 1) includes the sum of all the numbered areas that lie above and below the Long-run supply curve LR-Supply(C1, A0) to the left of Q_1” under the aggregate demand curve. The associated long-run costs for the pure effect of climate change (Row 2, Col. 2) include the sum of all the numbered areas under the same supply curve and to the left of the quantity Q_1”. The resulting sum for WTP less costs (CS+PS) for the pure effect of climate change (Row 2, Col. 3) is represented by the area, labelled 1, above the long-run supply curve LR-Supply(C1, A0) and to the left of the quantity Q_1”.

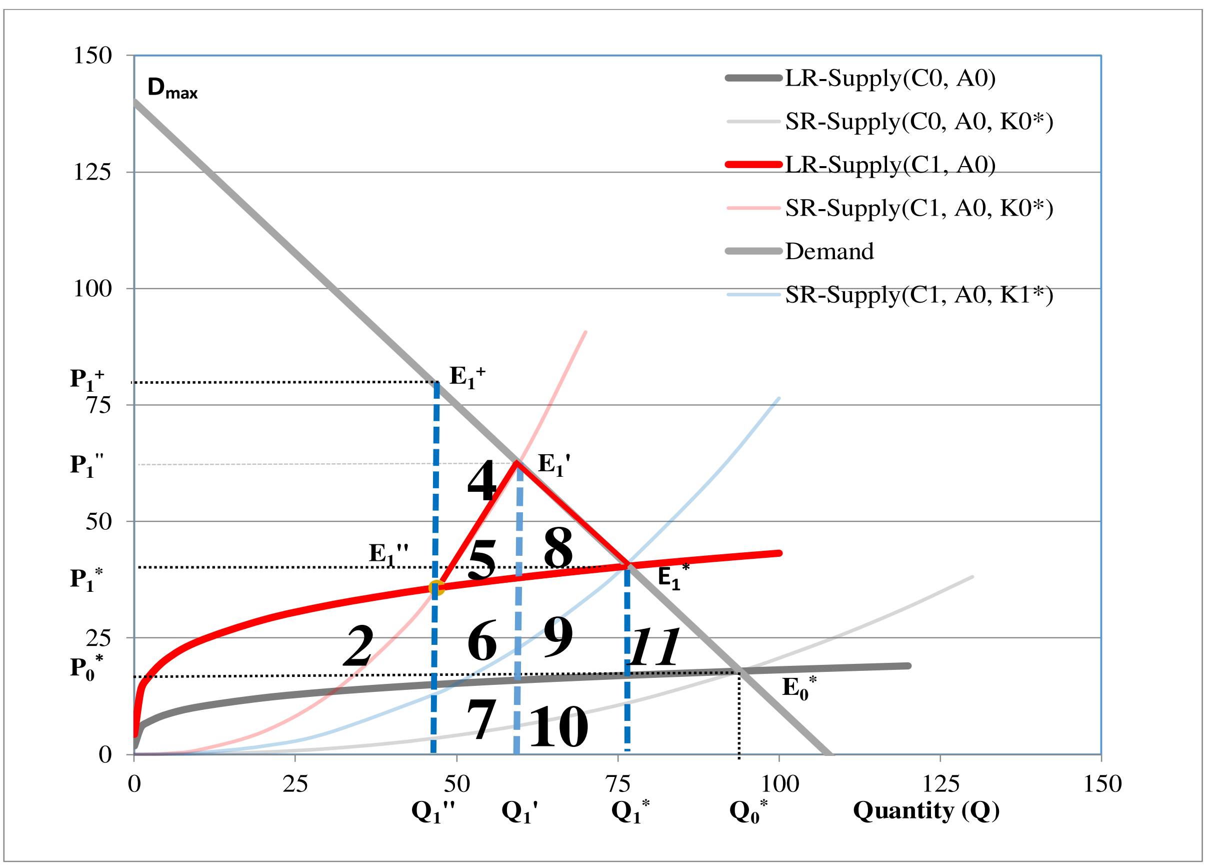
The difference between the WTP areas for the Base Case and the pure effect of climate change (Row 3, Col. 1) is represented by the sum of all the numbered areas that lie to the right of Q_1” under the aggregate demand curve. The difference between the cost areas for the Base Case and the pure effect of climate change (Row 3, Col. 2) consists of the sum of the three areas under the long-run supply curve LR-Supply(C0, A0) less the single area (2) that lies between the two long-run supply curves to the left of Q_1”. The final result (Row 3, Col. 3), which measures the CS+PS loss between the Base Case and the pure effect of climate change, includes the single area (2) between the two long-run supply curves and to the left of Q_1” plus the loss from the sum of the areas above the Base Case long-run supply curve, LR-Supply(C0, A0) to the right of Q_1”.

This means that, from the standpoint of climate change accounting, *the loss in the sum of the areas -(2+4+5+6+8+9+11), represents long-run climate change damages, as measured between the Base Case and the pure effect of climate change at* E_1*”*. The novelty of this result is that, at the very least, for a wide range of production functions used in applied economics, this is a measure of a no adaptation reference point from which short-run and long-run adaptation can be measured. It is the partial effect of climate change associated with the shift in the long- and short-run supply curves due to climate change, assuming only cost-minimizing behavior on the part of producers.

Figure 2.8 is intended to help illustrate the discussion that follows about the incremental effects of short- and long-run adaptation on welfare. It is a duplicate of Figure 2.7, except that it only includes the welfare areas that come into play under short- and long-run adaptation, namely the negative sum of the areas 4+5+6+7+8+9+10. It also includes two areas labelled in italics, ***2*** and ***11***, which represent the damages carried over from the pure effect of climate change. These are not incremental adaptation benefits or cost, nor are they affected by short- and long-run adaptation. However, they do come into play in an accounting sense, later, in Table 2.3 for measuring long-run residual damages. Thus, the focus of our discussion of the *incremental effects* of short- and long-run adaptation is concentrated on those areas that are subsumed by $Q_1''E_1^+E_1^*Q_1^*$.

This figure 2.8 not only will illustrate how short- and long-run adaptation avoids climate change damages, but also make it possible to illustrate how long-run adaptation provides greater net benefits of adaptation. In addition, once the net benefits of short-run and long-run adaptation have been identified, these can be deducted from the climate change damages to measure the residual damages of long-run adaptation. We first look at short-run adaptation and its effect on welfare. In the previous section on ‘short-run adaptation’ in this chapter, it was shown how, given the pure effect of climate change as a starting point, producers would have economic incentives to move up the short-run supply curve, SR-Supply(C1, A0, K0*), from the variable input mix implied at the point E_1'' to a stable market equilibrium point, thus eliminating the demand–supply price gap between the points E_1'' and E_1^+ in Figures 2.7 and 2.8. By moving up this short-run supply curve from E_1'' to E_1' producers can gain incremental benefits equal to the sum of the areas 4+5+6+7 in WTP terms. *These incremental benefits are, in fact, the short-run benefits of adaptation*. However, in doing so they incur incremental production costs equal to 5+6+7 under the short-run supply curve.[22] *These incremental costs are, in fact, the short-run adaptation costs.* This leaves an incremental net benefit for short-run adaptation that includes only the area, numbered 4, *which represents the short-run net benefits of adaptation*. The residual damages after short-run adaptation are equal to the sum of the areas that do not represent short-run adaptation, or: ***2***+4+5+6+8+9+***11*** - 4 = ***2***+5+6+8+9+***11***.

Figure 2.8. Illustrated Welfare Accounting for Short- and Long-run Adaptation.



22 Accounting for all costs using short-run supply curves can be tricky (Just et al., 1982). In this case, the costs labelled 6 and 7 are long-run costs and include capital costs and SRTC=LRTC at E_1''. While the segment of the short-run supply curve from E_1'' to E_1'' (area 5) includes just variable costs, the capital stock does not change, these variable costs being the only additional costs to 6+7.

The incremental net benefits of long-run adaptation are greater. In the previous section, it was pointed out that long-run adaptation consists of moving from point E_1" to the stable equilibrium point E_1* along the long-run supply curve LR-Supply(C1, A0, K1*). The incremental benefits of doing this in WTP terms in a static framework are equal to the sum of the areas 4+5+6+7+8+9+10, *which represents the long-run benefits of adaptation*. The long-run incremental costs are equal to the sum of the areas 6+7+9+10, *which represents the long-run costs of adaptation*. This leaves the sum of the areas 4+5+8 *as a measure of the long-run net benefits of adaptation.* Thus, in geometric terms, the net benefits of long-run adaptation are greater than the net benefits of short-run adaptation by an amount equal to the sum of the two areas, 5+8. *The damages that cannot be avoided are the long-run residual damages*. They are represented by the area between the two long-run supply curves, or ***2***+4+5+6+8+9+11 - (4+5+8) = ***2***+6+9+***11***, where the areas ***2*** and ***11*** are carried over from the pure effect of climate change.

These main results are presented below in Table 2.3 for both short- and long-run adaptation. Relative to short-run adaptation, the net benefits of long-run adaptation exceed those of short-run adaptation and reduce the residual damages of short-run adaptation by an equivalent amount.

Table 2.3. Incremental Effects of Short- and Long-run Adaptation on Climate Change Damages and Residual Damages.

Type of Adaptation	Climate Change: Net Damages (Without Adaptation)	Net Benefits of Adaptation	Residual Damages
Short-run	-(***2***+4+5+6+8+9+***11***)	4	-(***2***+5+6+8+9+***11***)
Long-run	-(***2***+4+5+6+8+9+***11***)	4+5+8	-(***2***+6+9+***11***)
Welfare improvements due to long-run adaptation, relative to short-run adaptation		+5+8	+5+8

Reference: See Figure 2.8

Having indicated the superiority of long-run adaptation from a welfare standpoint, a good question to ask is: why would a producer make a short-run adjustment to climate change as opposed to a long-run adjustment? The case-study literature on this topic that is needed to answer this question is spotty because most of the economics literature neglects talking about the differences between short- and long-run decisions and their implications for climate change. At the same time, a majority of the options that have been discussed in the physical and natural science literature take the form of short-run adaptation, such as crop selection, adjusting the cropping calendar, in situ moisture conservation and income diversification (Nhemachena & Hassan, 2007; Thomas et al., 2005 and 2007; Thornton et al., 2007 and 2010; Trærup & Mertz, 2011). However, there continues to be a great deal of interest in long-run measures, such as switching to supplemental or intensive irrigation, terracing, and agro-forestry, but rarely any comparison with reference to the relationship between short- and long-run adjustments (Bizoza & de Graaff, 2012; Chang et al. 2011; Hoch et al., 2012; Kibria & Saha, 2011; Kadigi et al., 2004; Laube et al., 2012 and 2008; Posthumus & Graaff, 2004). Only a few papers in any of these sets of literature have compared short- and long-run adaptation. In one such study, Callaway et al. (2008) found that changing the way in which water was allocated to urban and agricultural uses in the Berg River area of the Western Cape of South Africa could provide net adaptation benefits virtually identical to building the Berg River Dam, both of which could be considered long-run decisions and greatly exceeded the net benefits of changing operational rules. However, the study was deterministic.

A possible answer that is certainly being discussed, mostly outside the realm of economics, is the effect of risk and uncertainty on adaptation decisions, this being directly relevant to the question posed above. Long-run adaptation involves investment in capital stocks (and perhaps in new institutions, as well), whose "permanence" varies from some types of new farm implements in developing countries to large water-supply and flood-control structures in both developed and developing countries. Given the uncertainty associated with existing climate change projections (Boehlert et al., 2015; Deser et al., 2011; Hawkins & Sutton, 2009 and 2011), and also depending on how acute the need is to use these projections to plan and execute these long-run investments, the risk of planning for a climate that may not occur in the future may be very large and very costly. Two strategies to cope with this type of uncertainty (deep uncertainty) are to make investments that are operationally robust to many different planned projections (Jueland & Whittington, 2014; Kasprzyk et al., 2013; Lempert & Groves, 2010; Matalas & Fiering, 1977; Santini et al., 2013) or to wait for better information to avoid experiencing the cost of economic regret (Cameron, 2005; Golier & Treich 2003; Hobbs et al. 1997). In the latter case, short-run adaptation becomes an interim measure until more is known about climate change. However, this will come at a price, since dams, roads, beaches and resorts that were built based on the expectation of no climate change may lack the flexibility to respond to even moderate climate change. Thus, it would seem to be appropriate for project designers to focus on building considerable (perhaps even supra-optimal) short-run flexibility into whatever long-run measures are undertaken. This is the case for robustness over economic efficiency.

In the case of making investments that are operationally robust, one can look past current planning into the future once the investment has been made and exposed to future climates. In that case, it is the ex-post operational flexibility that makes the investment so valuable in ex-ante planning studies. Moreover, if this flexibility lives up to its future billing, it may well be the ex-post operational flexibility that provides the bulk of net benefits in the future. This is a vastly neglected area of short-run adaptation and brings to the fore the importance of combing long- and short-run flexibility.

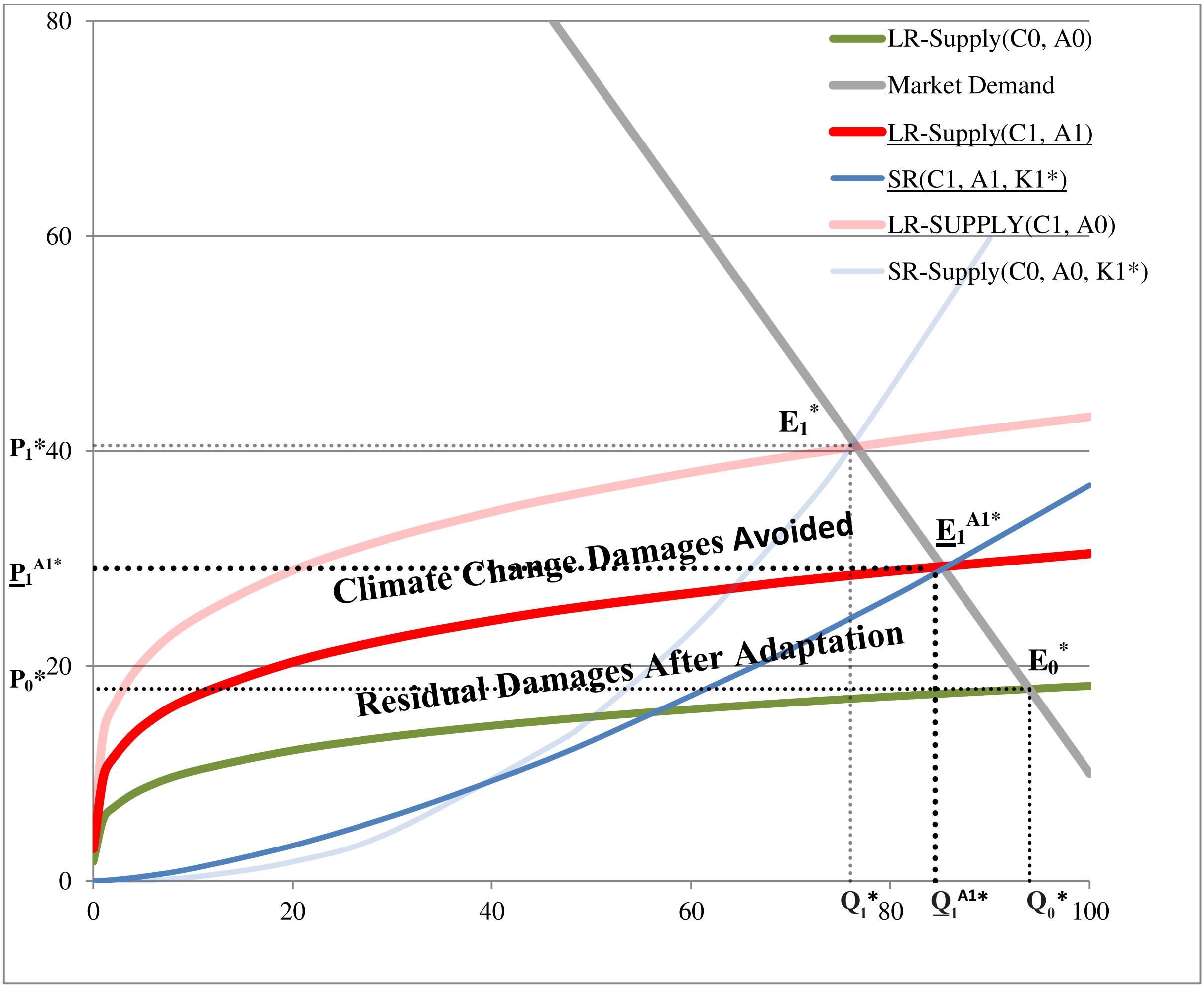
So far we have taken a somewhat limited view of long-run adaptation that omits changing the structure of production processes (i.e., the production function) and the design and operational parameters of these production functions. The reason for doing this was simple: to show that, even if the characterization of the suite of technologies used to adapt to climate change did not change, making long-run investments produces higher net adaptation benefits than short-run adaptation, provided of course that both sets of opportunities are available. In the next section, this assumption of static technology is relaxed, and we show that the long-run beneficial effects of altering the parameters of production processes can be substantially greater.

The Long-run Impact of Changes in Production Technology on Adaptation

In the "experiment" that follows, the parameters of the Cobb Douglas production function were changed to reflect greater possibilities for variable inputs to be substituted for capital. In this example, this might involve increasing grain storage capacity, adding a farm dam for supplemental irrigation, or building new roads to expand spatial linkages between points of production and consumption, all of which would give rise to different input substitution possibilities. The results are shown in Figure 2.9, which is truncated and contains fewer supply curves, compared to the previous two figures, to better illustrate the region (in the figure) in which adaptation adjustments take place.

The order in which this "technology change" is introduced affects the results. In this case we decided to look only at the long-run welfare impact of moving from the final equilibrium in the previous case, shown in Figures 2.7 and 2.8 at $E_1^*(P_1, Q_1^*)$, to a long-run market equilibrium associated with changing the production technology at $\underline{E}_1^{A1*}(\underline{P}_1^{A1*}, \underline{Q}_1^{A1*})$.[23] This long-run market equilibrium, like the two others depicted in the figure, are also minimum cost, where the corresponding short- and long-run supply curves intersect with each other. For the change in technology case, these two supply curves are, respectively, SR-Supply(C1, A1, K1*) and LR-Supply(C1, A1), where K1* is now optimal for both the change in climate, C1, and technology, A1.

Figure 2.9. Illustrated Effect of Changing Production Technology on Net Adaptation Benefits and Residual Damages



The main effects of changing the technology along with the variable and fixed factors along the long-run supply curve, LR-Supply(C1, A1), relative to the previous case are, first of all, a reduction in the price of maize from P_1^* to $\underline{P}_1^{A1*}$ along with an increase in output from Q_1^* to Q_1^{A1*}. Secondly, this reduces the residual damages. In the previous case, residual damages were equal to the area bounded by $0E_1^*E_0^*0$. However, the change in technology brings with it additional short- and long-run net benefits of adaptation, labelled "Climate Change Damages Avoided", equal to the area bounded by $0E_1^*\ E_1^{A1*}0$. Concomitantly,

23 A more complete adjustment, including both short- and long-run adaptation, was undertaken, but the illustration of this was difficult to execute, and a mathematical representation is beyond the scope of this report.

residual damages in the previous case are reduced to the area bounded by $0E_1^{A1*}E_0^*0$, labelled “Residual Damages after Adaptation”, an area about fifty per cent smaller than in the previous case. This illustrates the potential net benefits of adopting technologies that change the substitution opportunities between inputs in a way favorable to adaptation, allowing for a more economically efficient use of variable inputs and capital in the long run, compared to simply increasing the level of the capital stock associated with existing production processes.

Chapter Summary

This chapter began by presenting some of the definitions for adaptation to climate change used by several multilateral governmental institutions that have an important stake in preventing or avoiding climate change damages. We took the common points that all of them shared, and expanded on them to produce a purely economic definition:

Adaptation to climate change consists of the adjustments in resource allocation that economic agents[24] make in their consumption, production and investment decisions to avoid the economic losses, or to increase the economic gains, due directly or indirectly to the effects of climate change.

We also took issue with some of the "types" of adaptation that have been presented in the literature, particularly autonomous vs. planned adaptation. This is because, in practice, the definitions have varied so greatly and because, in an economic world, the actions of economic agents are always rational and purposeful. This may well be a somewhat narrow view based on recent critiques of neo-classical economic theory by social psychologists and experimental economists (Rabin, 1998). However, the definition provided in this chapter can be stretched pretty far, and it is not meant to imply that the only perspective for evaluating the benefits and costs of adaptation is neo-classical economics.

Using the economic definition of adaptation as a starting point, this chapter defined the important economic metrics that can be used to evaluate the benefits and costs of climate change in monetary terms: climate change damages, the net benefits of adaptation (avoided climate change damages) and the residual damages that are not avoided by adaptation. It then went on to show how the economic concepts of short- and long-run adaptation provide a powerful framework for evaluating these metrics. Using the example of maize production, presented in diagrammatic fashion, we showed how it was possible to identify a no-adaptation case, the pure effect of climate change, as a starting point for calculating climate change damages and the role of short- and long-run adaptation in reducing these damages. We then demonstrated how producers could either adjust their variable input use and move up their short-run supply curves to a market equilibrium, or alternatively adjust both capital stocks and variable inputs along their long-run supply curves to achieve a long-run market equilibrium. An analysis of welfare gains and losses due to both kinds of adaptation showed that long-run adjustment produced superior net adaptation benefits compared to the short-run adjustment path, even if this applied only to increasing the level of investment in the existing suite of technologies used to cope with climate variability. Finally, we showed how, by changing the structure and/or parameters of production processes and investing in new technology could further reduce climate change damages, compared to simply increasing the level of investment in existing technologies.

Using an example of maize production, we explored a number of aspects of short- and long-run adaptation. By minimizing both long- and short-run total costs subject to an output-constrained production function, we showed how exogenous changes in climate shifted both the short- and long-run supply curves. We found that for certain kinds of production functions, at the point of intersection between the short- and long-run supply curves, with and without climate, there was no change in total short- and long-run total costs. Thus, the input quantities in the Base Case and the climate change damage case did not change. However, production decreased. We called this the "pure effect of climate change", associated only with the effect of climate change on the short- and long-run supply curves of a producer due to total cost

24 Economic agents refers broadly to individuals, households and organizations involved in the production, consumption of, and investment in goods and services.

minimization. This point of intersection between the two supply curves is important because it makes it possible to isolate short- and long-run adaptation along either the short-run or the long-run supply curve.

We also showed how long-run adaptation involving changing levels in capital stocks increased the net benefits of adaptation compared to short-run adaptation where the capital stock is held fixed and only variable inputs can be changed. Finally, we showed how investing in new technology with different production parameters can further reduce climate change damages compared to simply changing the levels of investment in the existing capital stock.

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Newborn feet trapped and pushing a mosquito net

3. Bottom-up Economic Analysis: Simplified Methods

John MacIntosh Callaway, Jr.

The previous chapter was based on economic concepts and required a theoretical framework to explain them, as they apply to the economics of adaptation to climate change. To faithfully duplicate the concepts illustrated, especially in Figures 2.3 through 2.7, requires various kinds of economic models of supply and demand in product markets or firm-level process models. While numerous general and partial equilibrium models can be used to estimate the benefits and costs of adaptation at the global, regional, national and sectoral levels for developed economies, they often are not particularly useful at local scales to evaluate specific development or adaptation projects, and even when they are, it usually takes substantial effort to add specific adaptation options and features of the local economy. Finally, the local capacity to develop and implement these more sophisticated models does not exist in many developing countries. For example, some of the adaptation projects initially presented at workshops and submitted to the Global Environmental Facility under the National Adaptation Program (NAPA)[25] were inadequate for just these reasons and in many cases had to be redone by international experts to gain approval using more sophisticated economic models from global databases.

However, this does not mean that many aspects of the underlying framework for adaptation economics cannot be incorporated into simpler models and approaches using local data and enhanced local technical capacity. Two examples of this type of what we call a simplified "bottom-up" approach are represented by Callaway et al. (2010) for Montenegro and Callaway et al. (2011) for Macedonia, studies that were undertaken jointly by international and local experts to improve local technical capacity to address the economic impacts of, and adaptation to, climate change.

The primary objectives of this chapter are, first of all, to present a bottom-up approach for estimating the benefits and costs of adaptation, using spreadsheet models based on economic accounting principles overlaid by assumptions about economic behavior and market structure drawn from more sophisticated approaches. Secondly, the chapter aims to show a possible way to integrate concepts regarding the economics of climate change adaptation into policymaking, in particular by focusing on enhancing the capacities of local experts through applied and practical approaches.

Outlines of Top-down and Bottom-up Approaches

The terms "top-down" "bottom-up" have been used in a variety of ways by both economists and non-economists. Even in economic analysis, the use of these terms can sometimes be confusing. As used in economics, the term "top-down" generally refers to models in which one or more agents fully understand the system, typified by utility maximizing, forward-looking and fully informed agent(s) in modern macroeconomic models and partial equilibrium models (De Grauwe, 2009). The term "bottom-up", on the other hand, generally refers to models where no single agent has a complete picture of the total system

25 An outline of the NAPA program and links to NAPA plans submitted can be accessed online at http://unfccc.int/adaptation/workstreams/national_adaptation_programmes_of_action/items/7567.php

and therefore acts based on experience-based rules from a variety of different socio-cultural perspectives, often with limited information and a very short time perspective. In macroeconomics, this approach is typified by agent-based computational economics (Tesfatsion, 2002), and in the behavioral finance field is typified by Brock & Hommes (1997), Branch & Evans (2006), and De Grauwe & Grimaldi (2006).

However, in studies of the impacts of climate change and adaptation to climate change, these terms have taken on somewhat different meanings. In this context, top-down and bottom-up models are approaches to examining the linkages between climate change, the physical impacts of climate and their effects on production and demand. In top-down analysis, the linkages between climate change, physical impacts, production and demand are incorporated into aggregate production and demand functions, much as we have shown for the short- and long-run supply curves illustrated in Chapter 2. Integrated Assessment models (IAMs) fall into this category, as, generally, do Computable General Equilibrium Models (CGEs), as they combine and connect final demand, inter-industry flows of goods and services and sales to final demand and, finally, primary resource supplies through various "smooth" demand, profit and supply functions. Climate change and the physical impacts of climate change, as well as some forms of adaptation are, on the other hand, forced into CGE models exogenously. In bottom-up analysis the effects of climate change and the physical impacts of climate change, as well as the characterization of industry supply and demand, are, literally, built from the bottom-up, usually at the sectoral level, using process models. The process models are used to generate industry supply and demand curves, either by optimization or by simulation, while final demand is based either on smooth demand functions, engineering principles, or a combination of the two 'Partial Equilibrium (PE)' models of different economic damage sectors, such as energy, coastal property and infrastructure, agriculture and forests, and energy, which fall into this category. Examples of bottom-up and top-down models and the implications of differences in their structure for estimates of climate change damages and the net benefits of adaptation (although under different names) are discussed in Robinson et al. (2014) and von Lampe et al. (2014) as they relate to the agricultural sector.

Both type of models have been used in national and regional assessments of climate change impacts and adaptation to climate change. For example, two European Commission projects, Peseta I (Ciscar et al., 2011 and 2012) and Peseta II (Ciscar et al., 2014), used the GEM E-3 CGE[26] top-down model to convert the impact and adaptation results from various EU bottom-up partial equilibrium sectoral models to region-level welfare results. In addition, six CGEs and four partial equilibrium sector models are currently being used in the AgMIP global economic model intercomparison[27] related to climate change impacts and adaptation (see Robinson et al., 2014; von Lampe et al., 2014).

The Simplified Bottom-up Approach

The term "bottom-up" referring to models, as used here, fits into the latter framework as applied to analysis of the economic impacts of, and adaptation to, climate change. However, the way in which the supply and demand sides of these models reflect the effects of physical impacts and adaptation are constructed in a much simpler way in order to cope with the lack of technical capacity in LDCs to build full country- and project-specific PE models. These types of model can be compared to more sophisticated PE modeling approaches along several different dimensions, as follows:

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26 Online access at https://ec.europa.eu/jrc/en/gem-e3/model?searchdownload/GEMmodel.pdf

27 Online access at http://www.agmip.org/

1. ***Purpose of Model Use.*** More sophisticated, bottom-up PE models can be very useful in full-blown sector or multi-sector economic assessments of the economic impacts of climate change and adaptation, while the simplified bottom-up approach may be more useful to:
   - Be used as a training tool, to familiarize experts in different sectors with the concepts and calculation of climate change damages, the net benefits of adaptation and the residual climate change damages in a transparent way that is often not possible with more sophisticated, bottom-up PE models;
   - Conduct preliminary scoping analyses;
   - Identify vulnerable sectors and hotspots;
   - Reveal data and methodological problems and limitations in available information from existing economic models and empirical studies that are incorporated into these models and even into more sophisticated, bottom-up PE models, where local data from global data bases may be at odds with what is actually happening on the ground (which is usually better known to local experts);
   - To probe basic assumptions and results through sensitivity analysis; and
   - To identify gaps in technical capacity related to software and personnel.
2. ***Spatial and Time Scales.*** While more sophisticated, bottom-up PE models can be developed at the national, regional and global levels, the simplified bottom-up approach is best used at the local scale for specific projects or at the national scale for specific sectors. However, this means far less accuracy due to the lack of data and the inability to keep markets in equilibrium in a static, let alone a dynamic framework. PE models are extremely flexible for use, with different time scales ranging from days to centuries.
3. ***Damage Function.*** In more sophisticated, bottom-up PE methods damage functions are generally developed from engineering processes and bio-physical models suitable to the sector that is being affected by climate change and are then linked to key production parameters, such as crop yields in the agricultural sector, or to demand parameters, such as temperature in the case of residential energy demand. In the simplified bottom-up approach, these connections are external from a separate physical effects model, rather than internal, as is the case with the most sophisticated PE models. However, the level of spatial and temporal detail of the exogenous inputs to the damage function usually has to be re-aggregated using a variety of assumptions. In cases where a physical effects model is not available to generate the needed exogenous inputs to represent the physical effects of climate change, this gap can sometimes be bypassed if enough local data is available to estimate the parameters of empirical damage functions to substitute for the outputs of process or biophysical models of the damages caused by climate change. A less satisfactory but often used approach is to conduct a sensitivity analysis to approximate a range of physical effects drawn from the impacts literature.
4. ***Economic Model Structure.*** Bottom-up, PE methods typically employ economic representations of supply and demand, either normative (optimization) or positive (econometric), while a simplified bottom-up approach uses assumptions derived from micro-economics, but implemented in a spreadsheet, sometimes using simulation.
5. ***Capturing Market Effects.*** This is effectively a subset of bullet points 2 and 4. As illustrated in Chapter 2, climate change has the potential to influence both short- and long-run supply and demand curves[28] and thus market prices. These price shifts and their impacts on input use, production, consumption, investment and economic welfare can be incorporated into more sophisticated,

28 Demand curve effects of climate change were not illustrated in Chapter 2; however, an attempt to do so was made in the second example in this chapter.

bottom-up PE methods, especially in an optimization framework. However, in most cases a simplified bottom-up approach must assume that prices are exogenous. Even though it is possible to account for changes in variable and capital costs and preferences parametrically, it is generally not possible to capture the marginal effect on market prices and the effects of these impacts on production, consumption, investment and economic welfare, except through sensitivity analysis.

6. ***Capturing Climate Uncertainty.*** Capturing uncertainty in climate variables can be taxing to do computationally, both for top-down CGEs and bottom-up PE models. Climate uncertainty in these types of model can be simulated using Monte Carlo, or other sampling methods can be used to generate random distributions of otherwise deterministic inputs, such as the effects of higher temperatures on crop yields or the effects of reduced precipitation on runoff. The models are then run repeatedly (or looped) over the values of the resulting distributions and post-processed, using various assumptions, to get at the impact of climate uncertainty on important economic variables. In the case of PE models, objective functions can also be modified to reflect various types of decision-making under uncertainty. In the case of simplified bottom-up models, this process is actually simplified computationally, because Excel and some other types of spreadsheet software have built-in Monte Carlo features for converting and post-processing deterministic inputs into random inputs for different types of distribution. As a result, since nothing more advanced than a bit of algebra is generally included in the spreadsheet structure of a simplified bottom-up model, stochastic results are fairly easy to generate.

That said, a better understanding of the structure of simplified bottom-up approaches and how they can be used to estimate climate change damages, the net benefits of climate change and the residual climate change damages, or benefits, can best be illustrated by some deterministic examples, two of which are contained in the remainder of this chapter, focusing on the agricultural sector. Four more examples are provided in Chapter 4 so as to reflect the use of this approach in a wider variety of sectors.

An Example to Generalize From: Conservation Tillage in the Central Rift Valley of Ethiopia

The following case study was based on an attempt to use a bottom-up approach to determine whether there was sufficient information in existing published studies to estimate the net benefits of adaptation due to switching from conventional tillage to conservation tillage as a soil management practice for households growing maize in the Central Rift Valley of Ethiopia (Callaway, in press). In the end, it turns out that, for several reasons, this was not the case because there was no damage function information to show how these specific management practices differentially affects maize grain yields under climate change, nor was there any information to show how climate change might affect variable input use, and therefore the production costs, of either practice. However, negative findings like this can be useful and, while no attempt was made to follow up on this study using more recent literature, plugging these data gaps with hypothetical (made-up) information is useful for showing why it is so important in bottom-up studies.

The original study was based on information from three sources: Muluneh et al. (2015), who used a regional climate model to simulate rainfall and temperature for two of the SRES climate change scenarios in the region and then projected these impacts on maize yields; Kassie et al. (2014), who also simulated climate change in the region, but focused more intensively on simulating maize yields using two state-of-the-art bio-physical crop yield models and also looked at the physical impacts of several adaptation options (but did not include tillage practices); and Sime et al. (2015), who investigated the effects of existing climate variability on crop yields and the gross margins (profits) generated by switching from conventional tillage (CT) to two soil conservation practices, zero tillage (ZT) and minimum tillage (MT) in two areas in the region.[29]

29 Zero tillage options were far less competitive than the minimum tillage options, and so we exclude them here.

The main problem with these studies is that none of them combined climate change on the impacts of climate change on maize yields with an economic analysis that could be used to estimate climate change damages, the net benefits of adaptation and residual damages after adaptation for switching from conventional to conservation tillage. As a result, information from the first two sources were used to parametrically reduce yields by 5, 10, 20, 30 and 50 per cent for both sets of adaptation options and then use the information from the last study to make the economic calculations. Not surprisingly, what was evident in the base case – that there was only one conservation tillage option (minimum tillage with mulching) that could compete with conventional tillage practices – did not change in any of the climate change cases.

Table 3.1 presents the basic yield and revenue and cost data from Sime et al. (2015) for three CT and three MT options for the existing climate (Base Case). The conversion of physical units of inputs, such as days/ha for labor inputs, is translated into monetary units by a corresponding unit price in USD/ha. The calculation of revenues is made the same way, by calculating the average yield/ha times the unit price in dollars per ha. Gross margin, as defined in the study, is equal to the revenue received by the farmer less variable costs and the rental cost of oxen for plowing, or:

$$\text{Farmer Gross Margin/ha (Profit/ha)}_t = P_{maize,t} * Q_{maize,\, t} - \Sigma_i\, p_{it} * x_{it} - \text{rental cost of capital}_t \qquad \textbf{\textit{Equation 3.1}}$$

Where,

$P_{maize,\, t}$ = the unit price of maize in USD/ha year t,

$Q_{maize,\, t}$ = the maize yield in kg/ha in the year t,

p_{it} = the unit price of the i^{th} input for i = seed, fertilizer and labor in the year t,

x_{it} = the quantity of the i^{th} input in production in the year t, and

Rental cost of capital = Price of capital*interest rate*(1 -rate of inflation + rate of depreciation).

Table 3.1. Crop Budgets for Maize in the Central Rift Valley for Maize under Selected Conventional and Minimum Tillage Options.

		Conventional Tillage (CT)			Minimum Tillage (MT)		
Item	Unit Price	Mulch	No Mulch	Basin	Mulch	No Mulch	Basin
Maize Yield (kg/ha)		6375	5605	5534	5616	4475	4954
Total Revenue (USD/ha)	0.23	1466	1289	1273	1292	1029	1139
Input Cost (USD/ha)							
Seed	1.14	30	30	30	30	30	30
Fertilizer	0.73	78	78	78	78	78	78
Labor	1.64	57	60	81	60	67	93
Total Variable Cost (USD/ha)		165	168	189	168	175	201
Rental Cost (Oxen)		44	44	44	11	11	11
Total Cost (USD/ha)		209	212	233	179	186	212
Gross Margin (USD/ha)		1257	1077	1040	1113	843	927

Adapted from Sime et al. (2014)

What is needed next is information to alter Table 3.1 to reflect the differential impacts of climate change on maize yields and input usage. As previously indicated, no such source could be found, so we used a range of hypothetical yield reductions. However, before completing the analysis, it is worthwhile looking at the potential range of data sources from which such data can be drawn. Crop yield data sources include:

1. Consult local farmers.
2. Find a study or studies in the published academic literature, or in the Non-Annex 1 National Report, that have enough information about the impacts of climate on yields under alternative tillage practices to conduct a preliminary study.
3. Consult data published by federal agricultural institutions
4. Piggy-back your analysis on a directly relevant project or program that includes an investigation into the effects of climate change on crop yields under alternative tillage practices.
5. If the required information about the effects of climate change is not available from the above sources, then the only recourse is to:
    - Conduct or use results from controlled studies in greenhouses and/or field trials to assemble this information.
    - Simulate crop-yield impacts using a physically based crop model, for example, CERES-MAIZE (Jones & Kiniry, 1986), which requires extensive local, daily data on precipitation and temperature, local data on soil types, and parameters for drainage and percolation, etc. See Lobell & Burke (2010) for a discussion of the limitations of these models in development country settings.
    - Simulate crop yield impacts using a somewhat simpler model, like the FAO AquaCrop (Vanuytrecht, 2014), but which still has fairly extensive input data requirements.
    - Simulate crop yields using “trained” regression models from the CERES-MAIZE model, assuming one is available for the study location (see Lobell & Burke, 2010).

Data to estimate changes in production costs due to climate change are harder to find and usually have to be constructed from the bottom up using existing information about base case variables and capital inputs from:

1. Existing studies in the published literature,
2. Crop budgets available from federal agricultural agencies and agricultural economics institutions, and by
3. Consulting local farmers.

In this example, the existing crop budgets are modified to reflect the fact that conventional soil tillage methods, when faced with drier conditions, will face more rapid depletion of soil nutrients over time, thereby reducing yields. This will require additional fertilizer and more intensive plowing, thereby increasing the relevant cost components for conventional tillage methods. For costs, we assumed for illustrative purposes a 10% increase in fertilizer, labor and rental costs applied equally to all of the conventional tillage options to reflect additional tillage and fertilizer requirements. To simulate these effects for illustrative purposes, we used the given yield reduction (x per cent) and applied it to all of the minimum tillage yields equally, making no changes to production costs. For the conventional tillage options we assumed, again for illustrative purposes, that for any given percentage yield reduction (x per cent) applied to the base case yields and production costs, the following will apply:

For Yields:

- CT, No mulch yields = Base Case yields*(1-x%/100)*(1-10%/100)
- CT, Mulch yields = Base Case yields*(1-x%/100)*(1-8%/100)
- CT, Basin yields = Base Case yields*(1-x%/100)*(1-.5%/100).

Table 3.2. Comparison of the Impacts of Climate Change on Maize Yields, Revenue, Total Cost and Gross Margins Between the 20 and 30 per cent Yield Reductions from Callaway (in press) and this Study with Further Yield and Cost Modification to Conventional Tillage.

	Conventional Tillage (CT)			Minimum Tillage (MT)		
Item	Mulch	No Mulch	Basin	Mulch	No Mulch	Basin
Base Case (from Table 3.1): Both Studies						
Maize Yield (kg/ha)	6375	5605	5534	5616	4475	4954
Total Revenue (USD/ha)	1466	1289	1273	1292	1029	1139
Total Cost (USD/ha)	209	212	233	179	186	212
Gross Margin (USD/ha)	1257	1077	1040	1113	843	927
20% Yield Reduction: From Source Study						
Maize Yield (kg/ha)	5100	4484	4427	4493	3580	3963
Total Revenue (USD/ha)	1173	1031	1018	1033	823	912
Total Cost (USD/ha)	209	212	233	179	186	212
Gross Margin (USD/ha)	964	819	785	854	637	700
20% Yield Reduction: From Current Study						
Maize Yield (kg/ha)	4692	4036	4206	4493	3580	3963
Total Revenue (USD/ha)	1079	928	967	1033	823	912
Total Cost (USD/ha)	227	230	253	179	186	212
Gross Margin (USD/ha)	852	698	714	854	637	700
30% Yield Reduction: From Source Study						
Maize Yield (kg/ha)	4463	3924	3874	3931	3133	3468
Total Revenue (USD/ha)	1026	902	891	904	720	798
Total Cost (USD/ha)	209	212	233	179	186	212
Gross Margin (USD/ha)	817	690	658	725	534	586
30% Yield Reduction: From Current Study						
Maize Yield (kg/ha)	4106	3531	3680	3931	3133	3468
Total Revenue (USD/ha)	944	812	846	904	720	798
Total Cost (USD/ha)	227	230	253	179	186	212
Gross Margin (USD/ha)	717	582	593	725	534	586

The revised data do have a fairly substantial impact on relative gross margins, further penalizing the conventional tillage options compared to minimum tillage. The main questions, however, are how the adjustments made in this study affect climate change damages, the net benefits of adaptation and residual damages, as well as the relative profitability of the conservation tillage options. The latter is important because, ultimately, this will be an important determinant of whether any of the conservation tillage practices will replace conventional tillage under climate change conditions.

The information in Table 3.2 is all that is needed to perform the rest of the economic analysis.

Calculation of Climate Change Damages

In Chapter 2, we defined climate change damages as the loss in welfare due to climate change without changing the existing suite of practices used to adapt to climate variability. While conventional tillage dominates in the region, conservation tillage also plays a role in the Central Rift Valley. This means that, for each of the six tillage methods, the loss in gross margins due only to climate change (without switching tillage practices) is an appropriate measure of climate change damages. Thus, for each tillage method, the future value of climate change damages in some future period (t) can be calculated for each of the two damage scenarios as follows, using Eq. 1 from earlier in this chapter:

Climate Change Damages = $P_{maize} * Q(C1, A0)_{maize, t}$ - Total $Cost(C1, A0)_{maize, t}$ - [$P_{maize} * Q(C0, A0)_{maize, t}$ - Total $Cost(C0, A0)_{maize, t}$] ***Equation 3.2***

The results are shown in Table 3.3.

Table 3.3. Calculations of Climate Change Damage Comparisons for Two Yield Reductions from Callaway (in press) and this Study with Further Yield and Cost Modification to Conventional Tillage.

	Conventional Tillage (CT)			Minimum Tillage (MT)		
Item	**Mulch**	**No Mulch**	**Basin**	**Mulch**	**No Mulch**	**Basin**
Climate Change Damage: Base Case (from Table 3.1): Both Studies (USD/ha)						
Gross Margin (USD/ha)	1257	1077	1040	1113	843	927
Climate Change Damage: 20% Yield Reduction (USD/ha)						
From Source Study						
Gross Margin (USD/ha)	964	819	785	854	637	700
Climate Change Damage (USD/ha)	*-293*	*-258*	*-255*	*-259*	*-206*	*-227*
From Current Study						
Gross Margin (USD/ha)	852	698	714	854	637	700
Climate Change Damage (USD/ha)	*-405*	*-379*	*-326*	*-259*	*-206*	*-227*
Climate Change Damage: 30% Yield Reduction (USD/ha)						
From Source Study						
Gross Margin (USD/ha)	817	690	658	725	534	586
Climate Change Damage (USD/ha)	*-440*	*-387*	*-382*	*-388*	*-309*	*-341*
From Current Study						
Gross Margin (USD/ha)	717	582	593	725	534	586
Climate Change Damage (USD/ha)	*-540*	*-495*	*-447*	*-388*	*-309*	*-341*

The climate change damages results are in italics. In the original study, climate change damages were always higher for conventional tillage compared to the conservation tillage options. Not surprisingly, the simple adjustments to the yields and costs of conventional tillage methods made these differences even larger. However, these results are incomplete from an adaptation and profitability perspective.

Calculation of the Net Benefits of Adaptation

To make this calculation, a decision has to be made concerning which is the Base Case technology and what are the alternative tillage practices that represent real adaptation options. In the previous study, a decision was made that all three conventional tillage practices could be regarded as the base case since they represent standard practices in the region. Based on that selection, it was decided to include all of the alternative conservation tillage methods that could be regarded as adaptation options. This is in line with current, sustainable land use policy and is also a matter of some debate between traditionalists and environmentalists. Therefore, it is worth keeping.[30]

To calculate the net benefits of adaptation using the gross margin estimates, envisage a three by three matrix, such as the one below in Table 3.4, where the rows represent the three Base Case Technologies and the columns represent the adaptation options. In that case, each cell entry is the difference between the corresponding row entry (i) and column entry (j), computed with climate change.

Table 3.4. Adaptation Matrix, Illustrating the Adaptation Possibilities for Switching from a CT Base Technology to an MT Technology for Adaptation, Including the Net Benefits of Adaptation in Each Cell of Making a Change in Technology.

Base Case Technology	Minimum Tillage (MT) Adaptation Options		
	MT - Mulch	**MT - No Mulch**	**MT - Basin**
CT - Mulch	GM(MT-Mulch) - GM(CT-Mulch)	GM(MT-No Mulch) - GM(CT-Mulch)	GM(MT- Basin) - GM(CT-Mulch)
CT - No Mulch	GM(MT-Mulch) - GM(CT- No Mulch)	GM(MT-No Mulch) - GM(CT-No Mulch)	GM(MT-Mulch) - GM(CT-No Mulch)
CT - Basin	GM(MT-Mulch) - GM(CT-Basin)	GM(MT-Mulch) - GM(CT-Basin)	GM(MT-Mulch) -GM(CT-Basin)

In algebraic terms, each cell entry is calculated as:

$$\text{Net Benefits of Adaptation}_j = P_{maize} * Q(C1, A1)_{j/maize,\ t} - \text{Total Cost}(C1, A1)_{j/maize,\ t} - [P_{maize} * Q(C1, A0)_{i/maize,\ t} - \text{Total Cost}(C1, A0)_{i/maize,\ t}] \quad \textit{Equation 3.3}$$

Where i denotes rows and j denotes columns in Table 3.4.

The results are presented in Table 3.5, where these calculations involve differences in profits and represent the net benefits of adaptation.

30 Zero tillage options were ruled out for analysis in this report because they were far less competitive with conventional tillage options than were the minimum tillage options.

Table 3.5. Net Benefits of Adaptation of Switching from CT Base Case Options to MT Options for Two Yield Reduction Cases.

Base Case Technology (CT)	Minimum Tillage Adaptation Options (MT)		
	Mulch	No Mulch	Basin
Net Benefits of Adaptation: 20% Yield Reduction - Source Study (USD/ha)			
CT - Mulch	-110	-327	-264
CT - No Mulch	***35***	-182	-119
CT - Basin	***69***	-148	-85
Net Benefits of Adaptation: 20% Yield Reduction - Current Study (USD/ha)			
CT - Mulch	***2***	-215	-152
CT - No Mulch	***156***	-61	***2***
CT - Basin	***140***	-77	-14
Net Benefits of Adaptation: 30% Yield Reduction - Source Study (USD/ha)			
CT - Mulch	-92	-283	-231
CT - No Mulch	***35***	-156	-104
CT - Basin	***67***	-124	-72
Net Benefits of Adaptation: 30% Yield Reduction - Current Study (USD/ha)			
CT - Mulch	***8***	-183	-131
CT - No Mulch	***143***	-48	***4***
CT - Basin	***132***	-59	-7

Negative climate change damages in Table 3.5 mean that the MT column option is not competitive with the CT row option when competitiveness is based only gross margin calculations. Positive climate change damages (in bold italics) imply the opposite: the net benefits of adaptation are positive, and farmers have economic incentives to adopt the relevant MT soil tillage practice. However, it is also true that many households in the region are labor-constrained and cash-poor. This means that, where the negative difference is small, MT options may be preferable due to reduced labor and oxen rental costs, even though these options may have lower labor productivity than the CT options.

While the numbers jump around a bit, which is not surprising, given the somewhat arbitrary yield and cost adjustments, some conclusions can be drawn from this table:

- The most promising adaptation options from an economic and climate change perspective are to switch from CT-No Mulch and CT-Basin to MT-Mulch.
- However, switching from CT-Mulch and CT-No Mulch to MT-Mulch may become more attractive based on labor considerations as climate change damages increase.
- The above conclusions are more evident in both climate damage cases, for which yields were further reduced and costs increased in this study compared to the original study.

Calculation of Residual Climate Change Damages

In this example, the adaptation options were limited to switching from any of the CT options to any of the MT options. Thus, the climate change damages are associated with the CT option from which farmers can switch. Since many of the switching choices provided negative net adaptation benefits, it makes sense to exclude these from the calculations of the residual damages, since they only make the situation worse from an adaptation and economic point of view. Therefore, we report only the residual damages for the switching cases that involve changing from CT-No Mulch and CT-Basin to MT-Mulch.

Residual damages for the two switching cases from CT to MT are calculated as:

$$\text{Residual Climate Change Damages} = [P_{maize} * Q(C1, A1_{MT})_{maize,\, t} - \text{Total Cost}(C1, A1_{MT})_{maize,\, t}] - [P_{maize} * Q(C0, A0_{CT})_{maize,\, t} - \text{Total Cost}(C0, A0_{CT})_{maize,\, t}$$

Equation 3.4

The residual damages results are shown in Table 3.6, along with the calculations of climate change damages, the net benefits of adaptation and the per cent of climate change damages avoided by the adaptation switching options.

Table 3.6. Climate Change Damages, Net Benefits of Adaptation, Residual Damages and the Per cent of Climate Change Damages Avoided for Adaptation Switching Options.

	Technology for Adaptation: MT-Mulch			
Base Case Technology	**Climate Change Damages**	**Net Benefits of Adaptation**	**Residual Damages**	**% Damages Avoided**
	20% Yield Reduction - Source Study (USD/ha)			
CT-No Mulch	-258	35	-223	13%
CT-Mulch	-255	69	-186	27%
	20% Yield Reduction - Current Study (USD/ha)			
CT-No Mulch	-379	156	-223	41%
CT-Mulch	-326	140	-186	43%
	30% Yield Reduction - Source Study (USD/ha)			
CT-No Mulch	-387	35	-352	9%
CT-Mulch	-382	67	-315	18%
	30% Yield Reduction - Current Study (USD/ha)			
CT-No Mulch	-497	143	-352	29%
CT-Mulch	-447	132	-315	30%

The summary table (3.6) generally shows that the yield and cost changes introduced in this report did not alter the switching options from those arrived at in the source study, nor did it change the climate change damages by any appreciable amount for the two Base Case tillage practices. However, it did increase the net benefits of adaptation by a factor of about four in the CT-No Mulch to MT-Mulch case and roughly twofold in the CT-Mulch to MT-Mulch cases. However, the residual damages did not change dramatically between the two studies. What did change was the percentage of the damages avoided by adaptation, which were substantially higher in this study than in the original. This brings up an important point, namely that the importance of adaptation lies not in the absolute value of the net benefits of adaptation, but instead on the share of climate change damages it avoids.

Nevertheless, without actual data to represent the changes in yields and costs that result from climate change for all of the options, this study is suggestive only: the work still remains to be done. However, this study does show that, at least in parts of the Central Rift Valley where drying occurs, farmers will only have economic incentives to switch from conventional to conservation tillage if climate change has differential impacts on maize yields and production costs that favor conservation tillage by smaller decreases in gross margins than for conventional tillage.

In this example, all the calculations were made based on a single future time period. Thus, in all of the cases, the gross margin results for climate change damages, the net benefits of adaptation and residual climate change damages were expressed in future (undiscounted) values. In the next example, a case is presented in which capital investment plays an important role, and these metrics need to be evaluated in discounted terms over the period in which the investment produces benefits.

A Second Example to Generalize From: Rainwater Harvesting (RWH) by Small Freehold Farmers

This example focuses on the decision of small freehold farmers in areas of low rainfall to divert rainwater from an ex-situ catchment, store the water in cisterns, and then apply it to their fields as a way to supplement the production of row crops (maize in this case) using gravity drip irrigation. As in the previous case, the example is used to show how to construct the appropriate scenarios/cases needed to estimate the monetary values of climate change damages, the net benefits of adaptation and the residual damages that are not avoided by adaptation. In addition, the example is based on a fairly wide reading of papers covering the use of rainwater harvesting in the Central Rift Valley of Ethiopia (see, for example, Getnet et al., 2014; Halsema et al., 2011; Hartog, 2013; Kassie et al., 2013 and 2014; Moges et al., 2011; Yenesew & Tilahun, 2009). The data we use is partly hypothetical, drawn mainly from these sources. Nevertheless, we have relied heavily upon Hartog (2013) for information about the characteristics of the catchment area and cisterns, as well as economic information relevant to production and consumption on small farms in the region.

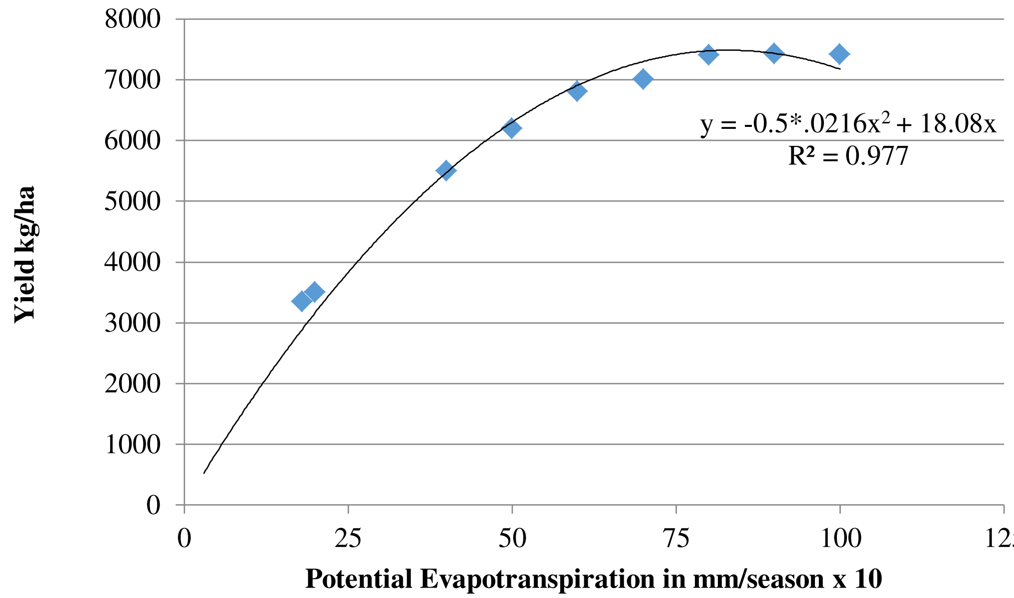
However, there are at least two general differences in this example from the previous one. First, it involves the economic analysis of both variable and capital costs, whereas the previous example looked only at variable costs. As such, this example brings to the fore the need to combine these two sets of costs and discount them over time. Second, while the example focuses mainly on private costs and benefits, it also looks briefly at the problem of accounting for technological externalities related to the impacts of upstream water diversions in a catchment on the supply of water available to downstream users. In this instance, some of the additional rainwater that is diverted from an upstream RWH catchment does not reach downstream farmers, as it would without RWH. This results in a potential loss of private market benefits to downstream water users.

Technical Efficiency of the Water Production Function

However, before turning directly to the example, we will look briefly at the more general question of the technical (and to a certain degree, the economic) efficiency of supplemental irrigation for agricultural production. The term technical efficiency, as used here, refers to the increased crop yield gained from adding supplemental irrigation to an existing rain-fed base from a fixed RWH catchment area. If the crop response function is nonlinear, the degree of technical efficiency achieved depends on the curvature of the water response function.

To show this we use a water response function, taken from Yenesew and Tilahun (2009) from the Rift Valley. The response function, developed in field trials, is presented in Figure 3.1.

Figure 3.1. Crop Water Response Function for Maize from the Rift Valley, Ethiopia.



The blue diamonds in Figure 3.1 represent the observed yields (on the vertical axis) obtained from the amount of crop water demanded (on the horizontal axis). The authors fit a linear response function to these data. However, we found that a quadratic function not only fits better, but also was more consistent with crop development. This is because the function exhibits an initial growth stage, characterized by declining marginal technical productivity, then reaches a maximum point of yield (equal to zero marginal technical productivity), after which the marginal physical product becomes negative, as yields decline. Unfortunately, there were not enough data points to estimate higher order polynomial functions efficiently. For the moment, we focus only on the performance of this response function under a "current climate". More will be said about the properties of the function under climate change later, when we get to the example itself.

Table 3.7 presents inputs levels (effective precipitation), output levels (yields), average efficiencies (output/input) and marginal efficiencies (d output/d input). Effective precipitation is the amount of precipitation that actually reaches the root zone of the crop where the water supplied is equal to the water demanded by the crop. The average effective precipitation for rain-fed agriculture is assumed to be 0.6 in this example.[31] Marginal efficiencies are captured by the first derivatives of the crop water response function at different levels of effective precipitation. For the quadratic response function, these first derivatives (dY/dX) are represented by a downward-sloping linear function of the form dY/dX =a + bX.

31 Thus, measured precipitation would be estimated by effective precipitation divided by 0.6.

Table 3.7. Average and Technical Efficiencies of Crop Response Function.

Effective Precipitation input (mm/season)	Average Annual Maize Yield (kg/ha)	Average Technical Efficiency (kg/mm)	Marginal Technical Efficiency (kg/mm)
0	0	0	18.08
100	1700	17.00	15.92
200	3184	15.92	13.76
500	6340	14.84	7.28
600	6960	13.76	5.12
837 (Physical optimum)	7364	12.68	0
900	7524	11.6	-1.36

Table 3.7 shows that, considering rain-fed agriculture only, additional precipitation provides the greatest physical benefit at initially low levels of average precipitation and low levels of output (yields), a situation that confronts many if not most small freehold farmers in many portions of the dry parts of semi-arid areas in Africa, such as the eastern portion of the Central Rift Valley. This is simply because the additional yields gained from increased precipitation are proportionally greater at lower than higher precipitation levels. Farmers who already have high yields will benefit less in terms of relative improvements in technical efficiency than those with lower yields. These technical benefits also result in higher relative economic benefits in the form of increased revenues from the sale of maize, but not necessarily in their profits (net benefits), since the calculation of profits must take into account higher capital costs incurred to construct the farm pond, cistern and drip irrigation systems and higher variable costs to operate and maintain them.

To get a broader picture of the role of technical efficiency in RWH, we need to look at how adding supplemental irrigation to a rain-fed system using RWH increases yields. This information is contained in Table 3.8.

The table needs a little explanation. Column 1 contains a range of average monthly maize growing season precipitation amounts available to rain-fed systems. Column 2 presents effective rainfall, using a coefficient of 60 per cent for each level of precipitation. The corresponding rain-fed yields are listed in Column 3. The water gaps, contained in Column 4, are simply the negative differences between rainfall and effective precipitation on a 1 ha of cultivated field. To find the RWH catchment area needed in any row to fill the gap in Column 4, one only needs to divide the gap by .85 to account for lower assumed losses in the RWH system compared to the rain-fed system (.85 under RWH vs. .60 under rain-fed conditions). Due to the averaging employed in this simple analysis, the gap in every case could be closed by a catchment area of .55 ha, given the existing rainfall amounts in Column 1. However, we wanted to make both the cultivated area and RWH catchment the same size for comparative purposes. The amount of effective rainfall from precipitation captured by the RWH system can be found by multiplying the average annual rainfall estimates in Column 1 by .85. These estimates are in Column 5. Column 6 combines the effective precipitation on the 1 ha cultivated area with the effective precipitation captured by the RWH catchment. Column 7 shows the maize yields that result from combining the rain-fed and RWH systems. Finally, Column 8 shows the percentage increase in yields due to adding supplemental irrigation from an RWH system.

Table 3.8. Calculation of Yields for Rainfed and Combined Rainfed + RWH from 1 ha, Current Climate

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
Average Annual Rainfall (mm[1])	Average Annual Effective Rainfall (mm[1])	Average Annual Rain-fed Yield (kg/ha)	Average Annual Water gap (mm[1])	Average Annual RWH supply from 1 ha catchment (mm[1])	Combined Rain-fed + RWH effective supply[2] (mm[1])	Average Annual Total Yield from combined systems (kg/ha)	% change in Yield, no Climate change
50	30	533	-20	42.5	72.5	1266	238%
100	60	1046	-40	85	145	2398	229%
200	120	2014	-80	170	290	4340	215%
300	180	2904	-120	255	435	5821	200%
400	240	3717	-160	340	580	6851	184%
500	300	4452	-200	425	725	7431	167%
600	360	5109	-240	510	870	7555	148%

[1] *mm per 5-month growing season, April through August*

[2] *Both the field and the RWH catchment areas are 1 ha*

This last result again emphasizes that the greatest physical and revenue benefits[32] from supplemental irrigation using RWH systems are obtained at the lower end of the water demand-yield spectrum. As in Table 3.7, as water inputs are increased, the percentage change in yields due to rain-fed, plus WH inputs to meet the crop water demand, falls as precipitation increases. As previously stated, this tends to benefit small freehold farmers (particularly those relying initially on rain-fed agricultural production in semi-arid places) more in relative terms than large farmers (particularly those farmers in areas with sufficient rainfall before adding RWH systems).

Framing the Example

The example presented here focuses on the calculation of the economic value of the adaptation benefits and costs of adopting RWH technology to supplement rain-fed production of maize by smallholder farmers. Table 3.9 presents the assumptions used in the analysis for rain-fed and RWH systems. The data presented here, both for households and agricultural production technology, is generally hypothetical, designed to characterize the situation of some of the poorest households in LDCs. The information on production costs was taken from Sime et al. (2015), while the estimate of the sale price of maize and costs were based on Hartog (2013).

32 Assuming exogenous and fixed prices for harvested crop yields, the revenue received from crop sales is simply the yield multiplied by a constant.

Table 3.9. Assumptions Used in the Analysis.

Household and Production Characteristics	Rain-fed System	RWH System
Crop grown (all cases)	Maize for household consumption and sale	Maize for household consumption and sale
Cultivated area (all cases)	1 ha	1 ha
Agronomic practice (Base Case)	Rain-fed agriculture, conventional tillage	1 ha catchment + storage cistern + gravity drip irrigation
Average annual maize consumption (demand)	350 kg/yr.	
Sale price of maize (all cases)	€0.27/kg.	
Average annual production (variable) costs[1]	€170/ha/yr.	€200/ha/yr.
Capital Costs	0.00	RWH: €800/ha loan, paid over 10 years

[1]*Labor cost is divided in half to reflect low marginal productivity*

To conduct the rest of the economic analysis, we need to tell a short story that is representative of small freeholder farmers in very dry parts of semi-arid areas in Africa. Under the Base Case, the household is not very well off: some years, the wet ones, bring higher production and net revenue, while dry years bring less production, revenue (and possibly consumption, although we had no way to account for this). In the worst years, the household may be entirely dependent on food aid from external sources. However, it is possible that the economic lot of the household can be improved by capturing rainwater from an ex-situ catchment in a cistern and then applying it to the crop by a very efficient means of irrigation (drip) to improve crop yields and provide higher net revenues for the household. We look at three cases in which the farmer invests in RWH supplemental irrigation. But we have to do this over time to take into account the effect of discounting future revenues and costs. We look at a "near future" time horizon for all cases, running from a base year (t=0) for thirty years to year t=30.

The "end game" of the analysis is to calculate the private economic value of climate change damages, the net benefits of adaptation and the residual climate change damages (or benefits) due to climate change and the RWH adaptation option.

The cases used here are conceptually identical to those used in the first example. The first case is the Base Case, for which most of the information is provided in Table 3.8. The Base Case assumes that prevailing climatic conditions remain constant over time in average terms. The second case is the Climate Damage Case, which involves the continuing use of a rain-fed system, but with a changing climate over time that increases the crop water requirement and reduces precipitation. The third case is the Adaptation Case. For this case, we assume that the farmer invests in the construction of a cistern to hold the harvested rainwater from a 1 ha ex-situ catchment, with the associated piping to connect the two, and a gravity drip irrigation distribution system to bring the water to the root zone of the crop.

Climate Change Impact Analysis

To put these various pieces together on the impacts side, the following information is needed:

- A water balance relationship over time between precipitation on the field and on the RWH catchment.
- Water extracted by maize plants for growth and development under rain-fed and RWH agricultural production technologies and residual losses.
- A regional climate/weather model to simulate the effects of climate change scenarios on local-scale catchments.
- A crop water response function that relates crop yield to plant water use, or Potential Evapotranspiration (PE) under varying temperature and precipitation regimes.
- A method for putting these three sources of information together to determine how changes in climate and production technology (i.e., rain-fed and RWH) affect crop yields *in a way that is helpful for an adaptation analysis*.

In actual practice, the hypothetical rainfall, supplementary irrigation and yield results, used in this example to provide input data for an economic analysis, would normally be developed by climate scientists and hydrologists working hand-in-hand with agronomists and crop yield modeling experts to generate daily or monthly precipitation amounts and the resulting crop yields for the various scenarios. The most important thing for an economist to know is what data are needed to conduct an adaptation assessment of climate change – not only the variables, but also the time and spatial scales of these data, as well as the periods for which it must be produced.

First, we constructed a hypothetical water balance involving the relationship between monthly crop water requirements, precipitation and supplemental irrigation through a RWH system, as described above. This information is presented in Table 3.10 for the Base Case to give a more complete point of reference than in Table 3.8.

Table 3.10. Crop Water Demand and Supply in the Base Case for Rain-fed and Supplemental Irrigation by a RWH System.

Growing season months	Crop water demand[1] (mm/mo)	Effective rainfall (mm/mo)	Effective irrigation needed to fill gap (mm/mo)	Effective irrigation from 1 ha catchment (mm/mo)	Effective rainfall + supplemental irrigation (mm/mo)
April	8.78	5.27	3.51	7.46	12.73
May	15.65	9.39	6.26	13.30	22.69
June	22.90	13.74	9.16	19.47	33.21
July	29.77	17.86	11.91	25.31	43.17
August	22.90	13.74	9.16	19.47	33.21
Total	100.00	60.00	40.00	85.00	145.00

[1] *Rainfall and crop water demand are assumed to be in equilibrium for the Base Case. Rainfall is reduced and crop water demand is increased in subsequent cases (see Tables 3.11 and 3.12).*

The hypothetical data in Table 3.10 cover a five-month growing season for maize in an area where rainfall is at the lower bound for rain-fed agriculture. While the underlying water demand function used in the analysis works on an annual basis, it was necessary to include finer time slices (monthly) to ensure that the simulated rainfall targets were met in each month for both rain-fed and RWH systems and to conduct a preliminary sizing analysis for the RWH cistern to determine the capacity of the RWH cistern to perform reliably.

Table 3.10 looks almost like Table 3.8, but has been simplified to focus on the water balance associated with rain-fed and RWH systems. The main results from this table are, first of all, the Base Case effective rainfall (Col.3), which, as previously indicated, represents 60% of the rainfall (Col. 2). The annual total for the growing season is 60 mm/yr. This annual total is used to drive the water response function for the Base Case, as will be indicated in the discussion of the next table, Table 3.11. The water response function used in the Base Case (and all other cases, with modifications for climate change) to derive the average annual maize yield is the same as used in the first part of this example and as shown in Figure 3.1, specifically: Maize Yield (Y) = 18.08* Water Input (X) - .5*.0216*[Water input(X)]^2.

Second, we find the effective irrigation from a one ha RWH catchment. As in Table 3.8, we keep the assumption that the area of the RWH catchment is one ha, the same size as the cultivated area[33]. The effective precipitation from the RWH catchment is equal to 85% of the rainfall (Col. 2), which amounts to 85 mm/yr. Finally, the total amount of precipitation + harvested water for supplemental irrigation is found in the last column (Col. 5). This is equal to the sum of: rainfall/.6 + rainfall/.85. The annual total for this input to the water response function is 145 mm/yr.

Table 3.11 shows how the changes in rainfall and the parameters of the crop water response functions were manipulated to reflect the impacts of climate change on crop yields for the Damage and Adaptation scenarios in which climate changes over time. The first two rows of Table 3.11 show how rainfall was reduced over time using an exponential function. The next set of rows show how the application of the rainfall function affected effective precipitation in the three cases used in the analysis over time. The last set of rows show the generalized crop water response function used to reflect the effect of both reduced precipitation and increased temperature on the yield of maize on a per ha basis.

The desirable properties of the crop water response function were hinted at earlier. We illustrate these with the aid of Figure 3.2. This figure is a plot of the yields produced by the hypothetical crop water response function in years 0, 12 and 24.

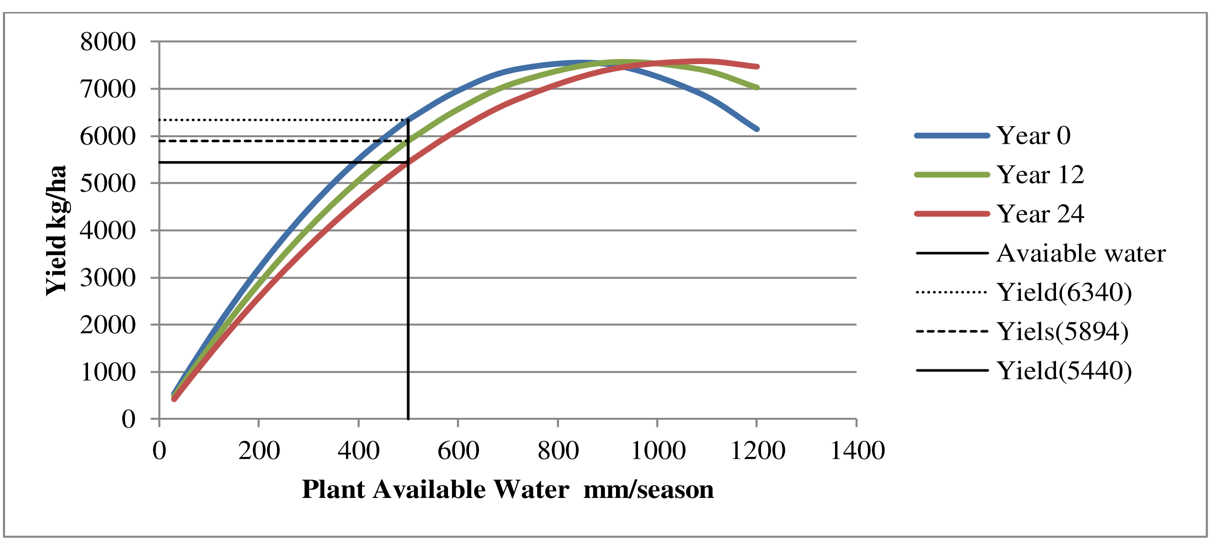
33 In actual practice, the physical size of the RWH catchment (and the RWH cistern) needed to achieve a specific yield target at the least cost would be optimized.

Table 3.11. Assumptions Used to Simulate Hypothetical Adverse Climate Changes over the next 30 years.

General Rainfall Function			
$X(t) = (1-.005)^{t} * X(0)$			
Years(t)	Effective Rainfall (mm/yr) Base Case	Effective Water Input (mm/yr)	
		Damage Case (Rainfall)	Adaptation Case (Rainfall +RWH)
0	60.00	60.00	145.00
6	60.00	58.22	140.70
12	60.00	56.50	136.54
18	60.00	54.82	132.48
24	60.00	53.20	128.57
30	60.00	51.62	124.75
General Crop Response Function			
$Y(t) = a(0)*(1-.01)^{t}*X(t) - .5*b(0)*(1-.02)^{t}*X(t)^{2}$			
Years(t)	**Response Function Parameters Evaluated over t**		
0[1]	$Y(0) = 18.08*X(0) - .5*.0216*X(0)^{2}$		
6	$Y(6) = 17.02*X(6) - .5*.0191*X(6)^{2}$		
12	$Y(12) = 16.06*X(12) - .5*.0169*X(12)^{2}$		
18	$Y(18) = 15.09*X(18) - .5*.0150*X(18)^{2}$		
24	$Y(24) = 14.21*X(24) - .5*.0133*X(24)^{2}$		
30	$Y(30) = 13.47*X(30) - .5*.0118*X(30)^{2}$		

[1] *The crop water demand function for year 0 is used for all years in t*

Figure 3.2. Crop Water Response Functions in Table 3.11 Evaluated for Years 0, 12 and 24 with Increasing Change.



Two main characteristics stand out in Figure 3.2. First, the maximum yield of the production functions, when evaluated over time, remains about constant, rising only slightly over time and requiring more water input to achieve the nearly fixed maximum.[34] Thus, it is assumed that temperatures do not become so high as to reduce yields, even given sufficient water inputs to meet crop water demand. Second, for a given level of water input, yields decrease over time, until close to the maximum yield. For example, assume that plant available water of 500 mm/season yields (6340 kg/ha) are highest in the initial year, decline in year 12 (5894 kg/ha), and decline further in year 24 (5440 kg/ha).

For this example, only one hypothetical climate change scenario was created, and the assumptions used to perturb both the precipitation amounts and response function parameters were stylized (as revealed in Table 3.11 and Figure 3.2) to reflect what might happen to both under increased temperatures and reduced precipitation. In any event, as previously indicated, it is not the job of economists to make these calculations. To perform the economic analysis a continuous time series from t(0) - t(30) was generated for maize yields. These data were required for the three different cases (Base Case, Climate Damage Case and Adaptation Case). The crop water response functions from the bottom panel of Table 3.11 were evaluated using the water input data for the three cases from the top panel of Table 3.11 for the entire study period. The results for the years t=0, 6, 12, 18, 24 and 30 are shown in Table 3.12.

Table 3.12. Hypothetical Average Annual Maize Yields for the Base Case, Climate Damage Case and Adaptation Case for Selected Years over a Thirty-Year Time Horizon.

	Average Annual Maize Yields (kg/ha/yr)		
Year	Base Case	Climate Damage Case	Adaptation Case
0	1042	1042	2395
6	1042	959	2206
12	1042	878	2030
18	1042	805	1867
24	1042	737	1716
30	1042	675	1577

Discounting

When performing economic analyses over time, it is generally accepted that future economic benefits and costs should be discounted back to the present to reflect either the opportunity cost of capital, social rates of time preference, or ethical values. There are many different theories and practices associated with discounting economic benefits and costs where climate change is involved (see, for example: Arrow et al., 1996; Dasgupta, 2008; Kaplow et al., 2010; Stern, 2008). However, most of these focus on different theories about the effects of climate change on social rates of time preference and/or the ethics of climate change policies. In the kind of bottom-up analysis used in this study, the main focus is on private benefits and costs. And, since a good deal of the adaptation actions that are occurring now and will occur in the future are not supported by external funding, it is more relevant to use discount rates that reflect the real opportunity cost of capital, as reflected by interest rates or rates of return associated with private-sector borrowing and spending by the economic agents who are undertaking the adaptation.

34 Ideally, the maximum yield of the function when evaluated with climate change over time would remain about constant, as long as higher temperatures were not limiting plant development and growth.

So, let us review this practice in straightforward mathematical terms in so far as it affects the net benefit function of private-sector agents. Modifying equation 3.1. to make it more general to fit this example, we get for both the future and the present value of net benefits, we arrive at:

Future Value (undiscounted) Farmer Net Benefit/ha_j = Σ_t [Revenue produced by the sale of maize in local $markets_{j,t}$ - Variable production costs of $Maize_{j,t}$ - Capital $Costs_{j,t}$] for all j. ***Equation 3.5***

Net Present Value (NPV)/ha_j = $(1+r)^{-t}$ * Σ_t [Revenue produced by the sale of maize in local $markets_{j,t}$ - Variable production costs of $maize_{j,t}$ - Capital $Costs_{j,t}$] for all j, ***Equation 3.6***

Where: j = rain-fed, RWH Production technology

t= 0,…, 30 Years

$Revenue_{j,t}$ = Sale Price of $Maize_t$*Quantity of Maize $sold_t$ for all j

Variable production cost of $Maize_{j,t}$ = Σ_i*Variable input $use_{i,j,t}$ for all j

Capital $Cost_{RWH,t}$ = Cost of RWH (Cistern + $Irrigation)_t$

r = opportunity cost of private capital

Thus, the only difference between the future and present value of net benefits is the discounting the time flow of future net benefits by $(1+r)^{-t}$ in each period.

Since we were concerned with private economic values that reflected actual farmer behavior, as opposed to optimal social behavior, the method of discounting capital costs followed conventional, real-life practices where the farmer borrows the money in year 0 at market rates of interest and then pays off the loan each year over a fixed period of time, which is not necessarily the same as the time horizon used in the analysis. In that case, the annual loan payment is calculated by the formula:

Annual (Annualized) Loan Payment on Capital $Cost_t$ = (Capital $Cost_0$*r)*$[1-(1+r)^{-T}]^{-1}$
for all t, ***Equation 3.7***

Where: T = the term of the loan on the Capital Cost

r = The actual loan rate

The capital costs for the materials and labor to construct the cistern and the gravity irrigation system were taken from Kesstra et al. (2013) and scaled to reflect the differences in the cultivated areas, the RWH catchment area and the cistern size. The estimated capital cost used in this study was €800/ha.

We estimated cistern size roughly for this study using an Excel spreadsheet to calculate the dynamic mass balance equation:

Daily Cistern Storage(t+1) = Daily Cistern Storage (t) - Daily Irrigation target(t) + Daily RWH input(t)
Equation 3.8

provided that if Storage(t+1) < 0, Storage(t+1) = 0, a system failure
Where t, in this case, represented each of 30 days for the five months of the growing season, or 150 days in all, and the daily RWH input per month (random, normally distributed variables transformed from mm/mo to m^3/day) and the daily irrigation target (fixed at daily averages for each month in m^3/day) were

based on Table 3.10 and the crop water response functions. In each of the simulations, it was assumed that there was 20 m^3 of water in the cistern at the start of each crop season, due to rain storage in the off-season months. The standard deviation for the RWH input was calculated in an arbitrary way that forced the coefficients of variation for each month to be the same over arbitrary values of 0.5, 1.0, and 1.5. One hundred thirty-year simulations for each of the 3 x 150 combinations of daily inputs were conducted. If a demand target was not met, it was counted as a system failure (see Eq. 3.8). After each simulation, the maximum storage size values were stored in a data base to indicate the required cistern size for each run, and the results were calculated on the basis of the stored data. As this was time-consuming, eventually, only the two highest coefficients of variation were used (1.0, and 1.5). Using the 1.0 coefficient of variation resulted in a cistern size that was 95 per cent reliable at 20 m^3/ha, while 99 per cent reliability required a storage capacity of just over 50m^3. The 1.5 coefficient of variation produced results that would have made RWH economically unfeasible, just by inspection, so these simulations were also truncated.[35]

The present and annualized values for revenues and variable production costs were estimated for the three scenarios (Base Case, Damage Case, and Adaptation Case) for 30 years using discount rates of 5, 10, 15 and 20 per cent. Annualized capital costs (the annual loan repayment amount) were estimated using a loan term of 10 years (Hartog, 2013) at the same four sets of interest rates.[36] The resulting Net Present Values and Annualized Values are shown in Table 3.13, while Figure 3.3 only presents the Net Present Value results in graphic form.

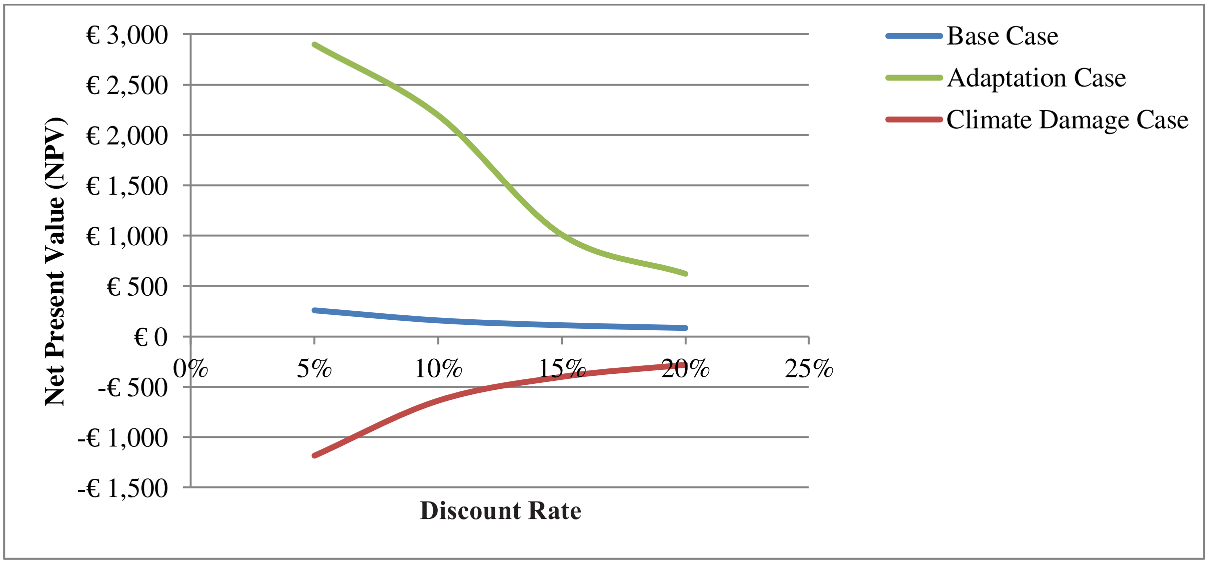
Table 3.13. Net Present Value (NPV) and Annualized Present Value (ANPV) for the Base Case, Climate Damage Case and Adaptation Case for Discount Rates of 5%, 10%, 15% and 20%.

Economic values	Net Present Value and Annualized Present Value of Three Cases at four discount rates (all values on a per €/ha basis)			
	5%	10%	15%	20%
Base Case (C0, Rain-fed)				
NPV	€ 259	€ 158	€ 111	€ 84
ANPV	€ 17/yr	€ 17/yr	€ 17/yr	€ 17/yr
Climate Damage Case (C1, Rain-fed)				
NPV	- € 1,184	- € 639	- € 402	- € 282
ANPV	- € 77/yr	- € 68/yr	- € 61/yr	-€ 57/yr
Adaptation Case (C1, Rain-fed + RWH)				
NPV	€ 2,899	€ 2,195	€ 1,010	€ 622
ANPV	€ 189/yr	€ 233/yr	€ 154/yr	€ 125/yr

35 This method is *not* recommended, but was interesting to try. It could have been performed quickly using a linear programming package of the sort hydrologists would use.

36 Something approaching 20% is probably more realistic for LDCs with local bank funding, although the lower rates might apply for programs sponsored by multi- and bilateral donors and financial institutions.

Figure 3.3. Net Present Value (NPV) for the Base Case, Climate Damage Case and Adaptation Case for Discount Rates of 5%, 10%, 15% and 20%.



The Base Case and the Adaptation Case show somewhat similar effects, declining NPV (in absolute terms) over time as the weight of the discount rates become heavier. The Climate Change Damage Case shows an opposite trend, with the damages decreasing (in absolute terms) over time. However, the phenomenon seen here is actually the same as in the previous two cases: the discount weights become heavier and reduce the negative net benefits (costs) over time.

Figure 3.3 also makes it possible to infer how the values of climate change damages, the net benefits of adaptation and residual climate damages change as the discount rate changes. At any given discount rate, climate change damages are the negative difference between the Base Case and the Climate Damage Case, and the net benefits of climate change are the difference between the Adaptation Case and the Climate Damage Case. Note, however, that the NPV of the Adaptation Case lies above both of the other two cases at every discount rate. Not only are the climate change damages completely erased, but there is also an area between the Adaptation and the Base Cases that is entirely positive. Therefore, in this case the residual damages are actually constitute positive benefits.

The information in Table 3.13 is all that is needed to calculate climate change damages, the net benefits of adaptation and residual climate change damages.

Calculation of Climate Change Damages

In Chapter 2, we defined climate change damages as the loss in welfare due to climate change without changing the existing suite of management practices used to adapt to climate variability, measured from the Base Case as the starting point. Thus, for this example, the production technology (rain-fed agriculture) does not change, but the climate does. Based on Equations. 3.6 and 3.7 in this example, the Net Present Value (NPV) and the Annualized Net Present Value ANPV of climate change damages can be calculated for each of the four discount rates as NPV(C1, Rain-fed) – NPV(C0, Rain-fed) from Table 3.13, which can be expressed as:

Net Present Value (NPV)/ha = $(1+r)^{-t} * \Sigma_t$ {Revenue[C1, A(Rain-fed)]$_t$ - Variable production cost[C1, A(Rain-fed + RWH)]$_t$ } - $(1+r)^{-t} * \Sigma_t$ {Revenue[C0, A(Rain-fed)]$_t$ - Variable production cost[C0, A(Rain-fed)]$_t$ }

Equation 3.9

ANPV/ha/yr[37] = {[Net Present Value (NPV)/ha]*r}*[1-(1+r)^-T]^-1
for T=30.

Equation 3.10

The results are shown in Table 3.14.

Table 3.14. Net Present Value (NPV) and Annualized Net Present Value (ANPV) of Climate Change Damage for Rain-fed Agriculture at Discount Rates of 5%, 10%, 15% and 20%.

Valuation Metrics	Climate Change Damage at four discount rates (all values on a per €/ha basis)			
	5%	10%	15%	20%
NPV	- € 1,443	- € 797	- € 513	- € 366
ANPV	- € 94/yr	- € 85/yr	- € 78/yr	- € 73/yr

Climate change damages, expressed in NPV terms, are negative at all discount rates and so are the annualized value of climate change damages. They both decrease over time in absolute terms), as the equal weight of discounting on both benefits and costs becomes heavier. The important lesson from this example, - assuming it were an actual case study, is that this climate change scenario will drive small freeholders into poverty and off the land they farm unless the household can make up their economic losses through employment in the locality or, as is more likely, in a distant city.

Computation of the Net Benefits of Adaptation

In Chapter 2, the net benefits of adaptation were defined as the climate change damages avoided by adaptation, measured from the Climate Damage Case as the starting point. If adaptation reduces (avoids) climate change damages, the result will be positive. Thus, in this example, both the climate and the production technology change. Using the same accounting approach for climate change damages in the previous section, the Net Present Value (NPV) and the Annualized Present Value of the net benefits of adaptation (ANPV) can be calculated as follows, as NPV[C1, A(Rain-fed + RWH)] – NPV[C1, A(Rain-fed)] from Table 3.13. This can be expressed as:

Net Present Value (NPV)/ha= $(1+r)^{-t} * \Sigma_t$ {Revenue[C1, A(Rain-fed +RWH)]$_t$ - Variable production cost[C1, A(Rain-fed + RWH)]$_t$ - Capital Cost[C1, A(Rain-fed + RWH)]$_t$ } - $(1+r)^{-t} * \Sigma_t$ {Revenue[C1, A(Rain-fed)]$_t$ - Variable production cost[C1, A(Rain-fed)]$_t$ }

Equation 3.11

ANPV/ha/yr[37] = {[Net Present Value (NPV)/ha]*r}*[1-(1+r)^-T]^-1 for T=30.

Equation 3.12

The results are presented in Table 3.15.

37 If both revenue and variable production costs are constant over time, then ANPV equals the constant value of Revenue - Variable production cost. In other words, the constant annual value = average value = ANPV.

Table 3.15. Net Present Value (NPV) and Annualized Net Present Value (ANPV) of Switching from Rain-fed Agriculture to a Combination of Rain-fed Agriculture plus Supplemental Irrigation under Climate Change at Discount Rates of 5%, 10%, 15% and 20%.

Valuation Metrics	Net Benefits of Adaptation at four discount rates (all values on a per €/ha basis)			
	5%	10%	15%	20%
NPV	€ 4,083	€ 2,834	€ 1,412	€ 904
ANPV	€ 266	€ 301	€ 215	€ 182

The net benefits of adaptation are positive for all discount rates, both in NPV and ANPV terms, meaning that adding supplemental irrigation through RWH provides additional income to the household from the sale of maize in local markets. More interestingly, both of these sets of values are always greater than those in the previous table. In other words, the net benefits of adaptation are always greater than climate change damages in this example. This has important consequences for the calculation of the residual climate change damages, because it will consist of two parts: first, the climate change damages avoided, and second, the additional private benefits in excess of climate changes.

Computation of the Residual Climate Change Damages

In Chapter 2, residual climate change damages were defined as the proportion of climate change damages that cannot be avoided due to climate change. Using the same accounting approach for residual climate change damages as in the previous section, the Net Present Value (NPV) and the Annualized Present Value ANPV of the residual climate change damages can be calculated as NPV[C1, A(Rain-fed + RWH)] - NPV[C0, A(Rain-fed)] from Table 3.13, which can be expressed as follows:

Net Present Value (NPV)/ha= $(1+r)^{-t}$ * Σ_t {Revenue[C1, A(Rain-fed + RWH)]$_t$ - Variable production cost[C1, A(Rain-fed + RWH)]$_t$ - Capital Cost[C0, A(Rain-fed + RWH)]$_t$} - $(1+r)^{-t}$ * Σ_t {Revenue[C0, A(Rain-fed)]$_t$ - Variable production cost[C0, A(Rain-fed)]$_t$ }

Equation 3.13

ANPV/ha/yr[37] = {[Net Present Value (NPV)/ha]*r}*[1-(1+r)^-T]^-1 for T=30

Equation 3.14

The results are presented in Table 3.16.

Table 3.16. Net Present Value (NPV) and Annualized Present Value (ANPV) Residual Climate Change Damages (Net Benefits) of Switching from Rain-fed Agriculture to a Combination of Rain-fed Agriculture plus Supplemental Irrigation by REW at Discount Rates of 5%, 10%, 15% and 20%.

Valuation Metrics	Residual Benefits at four discount rates (all values on a per €/ha basis)			
	5%	10%	15%	20%
NPV	€ 2,640	€ 2,037	€ 899	€ 538
ANPV	€ 172/yr	€ 216/yr	€ 137/yr	€ 108/yr

The results in Table 3.16 have already been explained graphically in Figure 3.3, but are worth repeating, as this is a case of residual benefits due to adaptation. The values presented her are the proportion of the net benefits of adaptation that is greater than the climate change damages[38] So, for example, using the results from Table 3.12 for the 5% discount case, we find the following. The NPV value of the private benefits of the freehold farmer in the Base Case is €259 (Table 3.13). The NPV value of the private benefits of the freehold farmer in Climate Damage Case is - € 1184 (Table 3.13). The resulting decrease in NPV, the climate change damages, is - €1443. The NPV value of the private benefits of the freehold farmer in the Adaptation Case is €2889 (Table 3.13). The resulting increase in NPV, the net benefits of adaptation, is €4083. Of this increase of €4083, the - € 1443 worth of climate change damages are completely avoided by switching to rain-fed + RWH agriculture. That leaves + €2640 as residual benefits, due to the fact that the net benefits of adaptation are greater than the absolute value of climate change damages. Thus, even if the climate does change as predicted in the single climate scenario, that is the amount of the increase from the Base Case net benefits the farmer would experience by switching production practices. If the climate did not change at all, the fact that the rain-fed + RWH option generates positive residual benefits (and not residual damages) means that it is a no-regrets option, yielding between € 2640 and € 538 in net benefits compared to the Base Case.

The Problem of Social Costs: Technological Externalities

In cases where the pattern of water diversion and type of use changes as an adaptive response to climate change, it will often be the case that, say, increases in diversions of water by upstream water-users to adapt to climate change will reduce the water available to downstream users in the same catchment, a negative technological externality. However, calculating the economic loss as a result of this externality is not a computationally easy exercise. This is because the calculation of even the private damages to downstream users due to this externality depends on the location of all the users relative to spatial run-off patterns, the proportion of consumptive use by all users and, therefore, the type of use, consumptive vs. non-consumptive.[39] Once this is information is known, it is possible to determine which downstream users are deprived of water and by how much.

38 The residual damage is zero, and these are additional benefits.

39 Consumptive use is the portion of water from a given diversion that is actually lost to the system and ranges from 0 (a non-consumptive use) to 1, where the range of values in between 0 and 1 involves consumptive use. If D is the amount of water diverted by a user and C< D is the consumptive use, the difference in return flow, R, lies within the positive range of D-C.

Take a very simple example of one upstream user and single downstream users on a river, where D_i is the amount of water diverted by each user, C_i is consumptive use, R_i is return flow, and r_i is the fraction of diverted water by each user is that is lost in consumption. In other words, $R_i = r_i*C_i$. In this example, if user 1 diverts one more unit of water from the river to adapt to climate change, then the supply of water available to the second user is equal to $1*(1-r_1)$. This represents a physical loss of water supply to user number 1, taking into account the higher diversion by the first user and the increased return from user 1 to user 2. Thus, the damage to user 2 would be equal to $(1-r_1)$*Marginal Value Product of Water for user 2 (MVP_2). If we considered N total users, then the total damages would be $1*(1-r_1)$ for user 2, $1*(1-r_1*r_2)$ for user 2, $1*(1-r_1*r_2*r_3)$, and so on. Furthermore, the exact valuation of the MVP of any user, even in this simple example, depends upon how water is allocated in the catchment (Callaway 1979; Hartman & Seastone, 1970), adding more complexity to the task of taking technological externalities into account in an adaptation analysis. In fact, the economically efficient allocation of stream flows in the presence of return flows is a theoretical construction developed by Hartman and Seastone (1970), refined to include compensation measures by Callaway (1979).

A Proposal

As earlier stated in the first part of this chapter, the simplified bottom-up approach was used by the staff of the UNEP-DTU Partnership[40] in two UNDP projects in Montenegro and Macedonia (Callaway et al., 2010; Callaway et al., 2011). The two projects were structured in the same manner. In the first phase of each project, URC staff met with staff from the country offices of UNDP. The purpose of these meetings was to identify both the important sectors in which climate played an important role and local experts in these sectors who could cover the physical impacts of climate change in these sectors, as well as sector-specific resource economists. In general, these sectors included agriculture, water resources, electric power generation and human health, although the coverage varied in both projects. In the next phase of the project, URC staff met with these local experts to design the methodologies for projecting climate change into the future, translating these changes into physical impacts in the relevant sectors, estimating the economic value of climate change damages (in Montenegro and Macedonia) and then estimating the net benefits of adaptation and residual climate change damages for selected adaptation projects that had been built into the case studies (primarily in Macedonia). In the process, a great deal of attention was paid to the availability of existing local data and models to execute the methodology. Important assumptions and short-cut methods for working around data gaps were also identified and agreed upon.

During the course of both projects, the local experts and URC staff reconvened several times in the countries to review progress and to resolve data and methodological issues. Draft final reports of the case studies were prepared by the local experts, reviewed by URC staff, and finalized by the local experts for review by UNDP. The finished case studies were then printed and published by the UNDP country offices. Lessons learned from these two studies are as follows:

- Highly qualified local experts were abundant both in simulating the physical impacts of climate change and in resource economics. In some cases, these groups of experts had collaborated before, but never on a study involving valuation of the physical impacts of climate change or the economics of adaptation.
- There were a number of model and data gaps that had to be filled in using existing proxy data, coupled with reasonable assumptions about the relationship between the non-existing physical

40 The name of the organization at the time was the UNEP-Risø Center (URC). This has since been changed to the UNEP-DTU Partnership (UDP).

effects models and any proxy data. In at least one case, a study of adaptation in the forest sector in Macedonia had to be dropped due to the lack of data to simulate better forest management.

- While the quality of the studies varied, due primarily to model and data gaps, the ambition of the local experts was high; the cooperation among economists, engineers and agronomists was excellent from the start, and the learning was quick.
- In both countries, the institutional capacity to integrate economics into public policy regarding climate change was limited.

We propose that this approach be improved to fit the qualifications and knowledge of local experts and that it be duplicated in LDCs. The cost of these types of studies is quite low. The two projects cited above were in the USD 20,000 to 30,000 range. However, these efforts did not include institutional capacity-building to take advantage of the research undertaken by local experts. Each country our staff has visited has a different set of institutional issues standing in the way of more complete integration. These can be stated in general terms as:

- Fragmentation and lack of communication between country offices organized under the United Nations Framework Convention on Climate Change (UNFCCC), sector-level ministries dealing with climate sensitive resources, and bilateral organizations like UNDP and UNEP.
- A lack of understanding of the concept of adaptation to climate change and the role of economics in adaptation decision-making at the national level.

Chapter Summary

The purpose of this chapter is to describe the relevant properties of a simplified, bottom-up approach for estimating the economic impacts of, and adaptation to, climate change and to compare them in a limited sense to more sophisticated, bottom-up PE models that are the current state-of-the-art. We suggested that many of the uses of these types of models were not only in helping experts in developing countries to understand how to compute climate change damages, the net benefits of adaptation and the residual climate change damages (or benefits) using a simplified, transparent approach, but also in identifying the model and data gaps in their countries needed to implement these types of models. These models can be used (and have been used) to conduct actual assessments of existing adaptation projects, more limited scoping studies of the economic impacts of adaptation to climate change, and preliminary sector-level scoping analyses at the national level, as well as to identify vulnerable sectors and hotspots.

The chapter also contained two hypothetical examples of how this approach could be used in the agricultural sector. The first example showed how an earlier study of switching from conventional to minimum tillage in response to climate in the Central Rift Valley of Ethiopia could be improved by taking into account the differential effects of climate change on these two tillage practices. However, this was a static model and did not include any dynamics due to the need to look at changes in capital expenditures over time and changes in crop yields over time. Both these aspects were incorporated into the second example, which looked at the adaptation benefits and costs of switching from rain-fed agriculture to supplemental irrigation through rainwater harvesting, again focusing on the Central Rift Valley. The net present value and annualized present value of climate change damages, the net benefits of adaptation and, in this case, the residual benefits due to the addition of rainwater harvesting were computed, including an analysis of the sensitivity of these values to variations in the discount rate. We also showed how it might be possible to account for the technological externalities that resulted from the impact of increased water use by upstream farms on those lower down in the catchment.

Finally, this chapter documents a process that would make it possible to integrate the economics of adaptation into the policy-making structure of LDCs by training local experts to perform case studies of adaptation through a hands-on approach, rather than relying so heavily on foreign experts alone. These case studies can be used for a small-scale demonstration of adaptation efforts, thereby paving the way for large-scale efforts. We also suggest that institutional capacity-building efforts aimed at advising national ministries about the role of economics in adaptation policy-making needs to take place in parallel with technical capacity-building efforts.

In the next chapter, we extend the use of the simplified bottom-up approaches to agriculture, infrastructure, environmental values and beach nourishment.

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4. Case Study Examples of Bottom-up Adaptation Benefit-Cost Analyses

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This chapter contains four case studies, the purpose of which is to illustrate how a simplified bottom-up economic analysis of adaptation options and projects can be implemented in less developed countries. These case studies cover rainwater harvesting in Tanzania, ecosystem-based adaptation in the Brazilian Amazon, reduction of cyclonic damage in coastal India, and beach replenishment in a hypothetical LDC setting.

As is the case with many types of multi-period projects, the benefits and costs differ from period to period, with capital costs often occurring in the first period and benefits and operating costs in later periods. This temporal asymmetry is usually taken into account by discounting future benefits and costs. Discount rates for the evaluation of climate policies, however, are a subject of intense debate, which goes far beyond absolute numbers to question the fundamentals of the discount rate. There is an entire spectrum between an empirically based i.e. a finance-equivalent discount rate and a social discount rate, i.e. the social welfare-equivalent discount rate (Goulder & Williams, 2012). Some authors, such as Stern (2007), have argued for using low discount rates based on the idea of preserving environmental quality for future generations. On the other hand, Nordhaus (2007) and Mendelsohn (2008) have criticized Stern, arguing that using low discount rates (below the observed opportunity cost of capital, adjusted for risk) leads to a misallocation of private resources and, in some cases, perverse outcomes, such as higher future consumption. This discussion can be further extended to determine whether the same discount rate is valid for the entire period. It is well known that individuals prefer payoffs sooner rather than later, the phenomenon of "hyperbolic" discounting. This is usually associated with great uncertainty about the future: "a bird in the hand is worth two in the bush". In that case, as Gouldner and Williams (2012) have suggested, a decreasing discount rate should be applied over time, but this applies to both discounting approaches.

Finally, we should note here that all the various arguments about discounting have been applied to mitigating greenhouse gas emissions and not to adaptation. In the case of adaptation projects, the benefits and costs are not temporally symmetric, so some form of discounting needs to be employed. However, in the large majority of cases (except for protection from sea-level rise), adaptation projects will be privately financed and will be relatively short-lived, recurring in nature. This is vastly different from dealing with greenhouse house emissions, with very long residence periods in the atmosphere, where many generations may be involved and there is also great uncertainty about the impacts on future generations. This suggests that, in the majority of cases, it is appropriate to discount future benefits and costs with observed rates of the opportunity cost of capital, or at the very least include a sensitivity analysis, using discounts from low to higher rates.

Rainwater Harvesting in Tanzania

This study focuses on the Dodoma area of Tanzania, where paddy rice production is threatened by seasonal shifts in rainfall patterns, and there is considerable uncertainty about the nature of the changes. The study explores expanded water-storage capacity with intra-seasonal soil moisture carry-over, using bunded basins (small earth embankments that contain irrigation water within basins, sometimes known as ridges, dykes or levees). Switching to the technology for adaptation increases yields far more than it increases fixed production costs. This results in net benefits that more than compensate for the expected damages over a ten-year period, while remaining highly profitable on a year-to-year future value basis.

Ecosystem-based Adaptation in the Brazilian Amazon

Large areas of the Amazon Basin in Brazil are being deforested at rapid rates, resulting not only in large greenhouse gas emissions, but also substantial loss of ecosystem services, such as flood control and non-timber forest products, the collection of fruits and nuts, small game hunting for household consumption and fishing opportunities, to name just a few. This study examines expanding protected areas through conservation and restoration to ensure that the forests still provide the provisioning goods and ecosystem services to help support smallholders facing unstable agricultural yields resulting from climate change. The results indicate that the net present value of the net benefits of expanding protected areas and avoiding climate change are about 1.5 times greater than the Base Case estimate of the value of the ecosystem services provided by the protected areas. Moreover, this option of conservation and restoration also avoids about 85 per cent of the climate change damages.

Reduction of Cyclonic Damage in India

Cyclonic storms in the Bay of Bengal are a frequent and can cause relatively large damage to infrastructure. For example, cyclone Hudhud in October 2014 is estimated to have caused USD 1.33 billion worth of damage to property and infrastructure in a single city, Visakhapatnam. While early warning systems adopted by the national and local governments have helped to reduce cyclone-related deaths, much can still be done to protect infrastructure. This study uses a combination of historical and hypothetical data to explore three adaptation options to reduce cyclonic damage to infrastructure: sea walls, expanding the existing area of mangrove plantations, and a combination of the two in a local district. The results indicate that the best approach from the standpoint of maximizing the net benefits of adaptation is to have a combination of these actions. Depending on the rate of discount, about 25 to 50 per cent of the climate change damages related to cyclones can be avoided. The associated net benefits of adaptation for this option range from about 1 to 2 billion US dollars.

Beach Replenishment to Enhance Tourism Revenues

Many developing countries, including quite a few LDCs, rely heavily on beach tourism to generate foreign exchange, service jobs and employment in other local industries. While the connection between coastal storms and climate change cannot be projected accurately by climate models, many costal beach areas worldwide experience varying degrees of beach erosion due to strong inshore currents. Moreover, sea-level rise will result in forcing these currents further inland. This case study examines a hypothetical group of beach vacation hotels that want to increase their revenues co-operatively by improving beach quality from its currently degraded level, using historical data to project increases in tourism due to beach nourishment, and simulated engineering data to determine the frequency (over time) and magnitude of the beach nourishment investments needed to achieve increased revenues. As in other case studies here, climate change damages, net benefits of adaptation and residual climate change damages are calculated. From the standpoint of an adaptation assessment, the estimated net benefits of adaptation over time are large. However, in part because the beach area was in such a poor condition prior to the beach nourishment program and the climate change damages were quite large, a non-climate-related Benefit-Cost Analysis was also conducted to determine the actual rate of return to investors. The results show that the rates of return were acceptable at low discount rates, but much lower, even negative, at discount rates that were closer to the actual opportunity costs of capital in many developing countries.

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Case Study 1. Rainwater Harvesting in Tanzania

Introduction

The current example focuses on the expansion of water storage capacity based on rainwater harvesting for paddy rice production, as the technology for adaptation that can be implemented by farmers with low cost. Paddy rice cannot be grown without irrigation, and rainwater harvesting systems are therefore already being used in small pockets today. However, efforts need to be scaled up in order to reduce the climate change effect from longer and dryer periods between rains.

Climate change is predicted to extend the period between rainfalls in Tanzania (Hulme et al., 2001). During dry seasons, dry spells with almost no rain are expected to become more common, while the number of high-intensity precipitation events appear to be increasing during the rainy season. Crop yields will most likely decrease if water is not stored during the rainy season even under the natural variability of climate, let alone climate change. Taking climate change into consideration, water availability will be scarcer during the dry season (which is longer and dryer), and the demand for water storage is increased compared to a situation without climate change. Potential adaptation options include increased water storage capacity and improved water management. If such adaptation options are integrated into the agricultural season planning process, improved water management can alleviate climate change damages from decreased rainfall during the growing season.

The economic assumptions in this example are based on a case study by Kadigi et al. (2004) of water availability for the irrigation of rice paddies and the impacts on crop yields in the Dodoma region of Tanzania. Dodoma's climate is characterized by a long dry season between late April and early December and a short single rainy season occurring during the remaining months. The average rainfall for the region is 574 mm, about 85 per cent of which falls between December and April (Tanzania Meteorological Agency, 2006). Rainfall is rather unpredictable in frequency and amount, and climate change is expected to increase this uncertainty. The unreliability of rainfall imposes a pattern of risk aversion in agriculture and is a serious constraint on present efforts to improve crop yields. Precipitation is predicted to increase by 5-30 per cent during the rainy season and decrease by 5-10 per cent during dry months for year 2030 in Tanzania, and the interior part of the country especially will experience temperature increases and longer dry periods (Clark et al., 2003; Hulme et al., 2001). The Dodoma region will not remain untouched by the phenomenon, and some studies, including that by the NAPA, reinforce the assumption of an increase in rainfall anomalies (Tumbo et al., 2007; NAPA, 2007).

With climate change, rainfall in Dodoma is assumed to decrease by 10 per cent during the dry season and increase by 20 per cent during the rainy season. Total rainfall is thus assumed to increase, but the dry period is likely to become dryer and the rainy season is likely to become wetter. This is illustrated in Table 4.1.1, which shows that total rainfall is likely to increase, but there will be greater variation between the rainfall in the dry and wet seasons respectively.

Table 4.1.1. Historical and expected future rainfall in Dodoma region. Based on Tanzania Meteorological Agency (2006).

	Rainfall in millimetres, historical trend (1974 – 2004)	Rainfall in millimetres, expected future trend (2030) with climate change
Total average rainfall, rain season	488	586
Total average rainfall, dry season	86	77
Total rainfall	574	663

Analysis

The analysis in this case is divided into assessing the net benefits in the base case, damage case and adaptation case. In line with the conceptual definitions in Chapter 2, the Base Case is defined as the situation with existing technology and current climate. The Damage Case is the situation where the climate changes (in this case adversely), while the technology does not change. The Adaptation Case is the situation where the climate changes, but a technology for adaptation is also adopted. The assessment has been done for ten years. The discount rates are assumed to be in the range of 7 to 15 per cent. The revenues and costs change in every case, but they are assumed to be same annually within each case situation. In the subsequent sub-sections, we assess the technology for a ten-year period which is the assumed technology life span.

Base Case

For Dodoma region, the base case (Table 4.1.2) will be the crop budget for the cultivation of paddy rice with the traditional technology (the existing excavated bunded basin) and the current climate. The net present value (NPV), based on gross margins, for the total result of the Base Case is calculated from the gross margins estimated in the crop budget and is shown in the last row of Table 4.1.2.

Damage Case

Water shortages limit the quantity and variety of crops, and also have a negative influence on the possibilities for enhanced crop or livestock production in relation to emerging markets. Water shortages, therefore, represent a key barrier to poverty reduction in rural areas. Crop yields generally depend on climate variables like temperature and precipitation. These relationships between temperatures, precipitation patterns and crop yields have been well established in a number of studies. These precise relationships between the magnitude of the variable and crop yields are very context specific. For e.g. yields in the US will depend on the crop, specific geographic location, specific climate conditions and other factors like soil types etc. (Meertens et al., 1999; Mohamed et al., 2002; Rosenzweig et al., 2001). Therefore, there is some uncertainty about the relationship in Tanzania. More frequent droughts and decreased water availability during the dry months will shorten the growing season and reduce crop yields. Few studies have been done for Tanzania, and the existing studies do not integrate climate change considerations or take into account increased variability in precipitation patterns (Hatibu et al., 2006; Kadigi et al., 2004; Senkondo et al., 2004). The existing studies follow the historical trends in rainfall variability and do not consider or prepare for increased rainfall variability or increased demand for extended water storage capacity.

Table 4.1.3 below is a revised crop budget that reflects a decrease in crop yields as a result of expected climate change with more frequent droughts and decreased water availability during the dry months. This case represents the ‘Damage Case’ with a variable climate and the technologies remaining the same. The NPV, based on gross margins, for the revised crop budget is presented in the last row of Table 4.1.2.

The results in Tables 4.1.2 and 4.1.3 show that the difference between the base case and the damage case could range from -USD 3,013 to -USD 2,153, depending upon the discount rate. This value also gives an estimate of the climate change damages.

Table 4.1.2. Costs and Benefits (Base Case) of Rice Paddy Production with Base Technology and Current Climate. The Calculations are Based on Data from Lazaro et al. (2000) and Kadigi (2003).

			Total value per year USD (2000 prices)					
	Units	Price/unit	Year 1	Year 2	Year 3	....	Year 9	Year 10
			Revenue					
Yield (kg/ha)	4000	0.20	0.20	781.25	781.25	-do-	781.25	781.25
Total Revenue (USD/ ha)(not discounted)				*781.25*	*781.25*	-do-		*781.25*
			Costs					
Maintenance cost of existing water storage			10.68	10.68	10.68	-do-	10.68	10.68
Plot renting (USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Seeds (kg/ha)	24	0.25	0.25	6.00	6.00	-do-	6.00	6.00
Fertilizer (bags/ha)	2	18.75	18.75	37.50	37.50	-do-	37.50	37.50
Tractor hiring charge(USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Hired labor (days/ha)	39	1.25	1.25	48.75	48.75	-do-	48.75	48.75
Family labor (days/ha)	183	0.33	0.33	61.08	61.08	-do-	61.08	61.08
Bags and twine	10	0.88	0.88	8.75	8.75	-do-	8.75	8.75
Transport				10.00	10.00	-do-	10.00	10.00
Total Costs (USD/ha)(not discounted)				*258*	*258*	-do-	*258*	*258*
Gross Margin (USD/ha) *(not discounted)*				**523**	**523**	-do-		**523**
Average farm/plot size	0.7		366	366	366		366	366
Gross return to an average plot (USD)								
Estimated annual volumetric water demand (use) (m^3 per ha)	13731		13731					
Estimated annual volumetric water demand for an average farm size of 0.7 ha (m^3)	9611.7		9612					
Productivity (value) of water (Kg/m^3)	0.13		0.29					
Productivity (value) of water (USD/m^3)		0.20						
Discounted Net Benefits @ 7% in USD	3,673			Discounted Net Benefits @ 15% in USD				2,625

Table 4.1.3. Damage Case (Climate Change) with Base Case "Technology" and Climate Change. Costs and Benefits of Rice Paddy Production with Existing Rainwater Harvesting System, Assuming Climate Change and Base Technology for Adaptation. The Calculations are Based on Data from Lazaro et al. (2000) and Kadigi (2003).

			Total value per year USD (2000 prices)					
	Units	Price/unit	Year 1	Year 2	Year 3	....	Year 9	Year 10
Revenue								
Yield (kg/ha)	1800	0.20	351.56	351.56	351.56	-do-	351.56	351.56
Total Revenue (USD/ha)(not discounted)			351.56	351.56	351.56	-do-	351.56	351.56
Costs								
Maintenance cost of existing water storage			10.68	10.68	10.68	-do-	10.68	10.68
Plot renting (USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Seeds (kg/ha)	24	0.25	6.00	6.00	6.00	-do-	6.00	6.00
Fertilizer (bags/ha)	2	18.75	18.75	18.75	18.75	-do-	18.75	18.75
Tractor hiring charge(USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Hired labour (days/ha)	39	1.25	48.75	48.75	48.75	-do-	48.75	48.75
Family labour (days/ha)	183	0.33	61.08	61.08	61.08	-do-	61.08	61.08
Bags and twine	10	0.88	8.80	8.80	8.80	-do-	8.80	8.80
Transport			10.00	10.00	10.00	-do-	10.00	10.00
Total Costs (US$/ha)(not discounted)			*258*	*258*	*258*	-do-	*258*	*258*
Gross Margin (USD/ha) *(not discounted)*			**94**	**94**	**94**	-do-	**94**	**94**
Average farm/plot size	0.7							
Gross return to an average plot (USD)			66.00	66.00	66.00	-do-	66.00	66.00
Estimated annual volumetric water demand (use) (m^3 per ha)	13731							
Estimated annual volumetric water demand for an average farm size of 0.7 ha (m^3)	9612							
Productivity (value) of water (Kg/m^3)	0.13							
Productivity (value) of water (USD/m^3)		0.20	0.03	0.03	0.03	-do-	0.03	0.03
Discounted Net Benefits @ 7% in USD	660		Discounted Ned Benefits @ 15% in USD					472

Technology for Adaptation

Potential technologies for adaptation to reduce the effect of changes in rainfall patterns on crop yields include rainwater storage for irrigation, adjustment of planting dates, changes in fertilization, introduction of new crop varieties and location, application of conservation tillage, and reduced utilization of marginal lands. When considering water conservation from a programme perspective or designing measures to increase the incentives to adopt technology, a comparison between these technologies may be needed to assess those that meet the criteria in the best possible way. This example focuses on an expanded water storage capacity, which is obtained from an extension of an existing excavated bunded basin, a method of run-off utilization, and the management and storage of water for paddy rice production. The expansion is constructed by digging to a depth of 0.2 to 0.5 meters, using the scooped soil to build a bund around the field perimeter (Lazaro et al., 2000). Construction costs are amortized over a life-time period of ten years assuming 10 per cent annual maintenance costs. The only construction inputs are land and labour. The cost of the land is assumed to be zero, while labour is assumed to be provided by family members having low opportunity costs, especially if the work is carried out during the slack season. The cost of hired labour used in peak seasons for sowing and harvesting is valued based on the opportunity cost of labour used in a study of rainwater harvesting in Tanzania (Senkondo et al., 2004). The technology (extension of an existing excavated bunded basin) is expected to have a lifetime of more than twenty years. We assess the net benefits for ten years as being consistent with the assumptions.

Adaptation Case

Table 4.1.4 contains a revised crop budget that includes the adaptation technologies described above. The discounted values of net benefits are presented in the last row of the table.

Table 4.1.4. Adaptation Case. Costs and benefits of rice paddy production with expansion of an existing rainwater harvesting system, assuming climate change and technology for adaptation. The calculations are based on data from Lazaro et al. (2000) and Kadigi (2003).

			Total value per year US$ (2000 prices)					
	Units	**Price/unit**	**Year 1**	**Year 2**	**Year 3**	**....**	**Year 9**	**Year 10**
			Revenue					
Yield (kg/ha)	3000	156.25	585.94	585.94	585.94	-do-	585.94	585.94
Total Revenue (USD/ha) (not discounted)			585.94	585.94	585.94	-do-	585.94	585.94
			Costs					
Investment cost, water storage (man days, family labour)	320	0.33	106.80					
Maintenance cost of water storage			10.68	10.68	10.68	-do-	10.68	10.68
Plot renting (USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Seeds (kg/ha)	24	0.25	6.00	6.00	6.00	-do-	6.00	6.00
Fertilizer (bags/ha)	2	18.75	18.75	18.75	18.75	-do-	18.75	18.75
Tractor hiring charge(USD/ha)	1	37.50	37.50	37.50	37.50	-do-	37.50	37.50
Hired labour (days/ha)	39	1.25	48.75	48.75	48.75	-do-	48.75	48.75
Family labour (days/ha)	183	0.33	61.08	61.08	61.08	-do-	61.08	61.08
Bags and twine	10	0.88	8.80	8.80	8.80	-do-	8.80	8.80
Transport			10.00	10.00	10.00	-do-	10.00	10.00
Total Costs (USD/ha)(not discounted)			*365*	*258*	*258*	-do-	*258*	*258*
Gross Margin (USD/ha) *(not discounted)*			**221**	**328**	**328**	-do-	**328**	**328**
Average farm/plot size	0.7							
Gross return to an average farm (USD)			154.97	229.73	183781	-do-	183781	183781
Estimated annual volumetric water demand (use) (m^3/ha)	13731							
Estimated annual volumetric water demand for an average farm size of 0.7 ha (m^3)	9612							
Productivity (value) of water (Kg/m^3)	0.22							
Productivity (value) of water (USD/m^3)		0.20	0.04	0.04	0.04	-do-	0.04	0.04
Discounted Net Benefits in USD @ 7%	2,204		Discounted Net Benefits in USD @ 15%					1,553

A comparison of the damage and adaptation cases (Tables 4.1.3 and 4.1.4) shows that, compared with the damage case, there is an increase in the net benefits of adaptation (average gross margins) from USD 94 per hectare to USD 221 in the first year with adaptation and that this gain increases in subsequent years, since all the construction costs fall in year 1 (see also Table 4.1.4). The extended rainwater harvesting system implies a very large increase in the yield, from 352 kg/ha without adaptation to 586 kg/ha with adaptation.

Estimates of Climate Change Damages, Net Benefits of Adaptation and Residual Damages

The NPVs for the 'Base Case', the 'Damage Case', and the 'Adaptation Case' are used for calculating climate change damages, net benefits of adaptation and residual damages. The results are shown in Table 4.1.5 below. The algebraic definition of these metrics is:

Climate Change Damages = Damage Case NPV – Base Case NPV.

Net Benefits of Adaptation = Adaptation Case NPV – Damage Case NPV.

Residual Damages = Adaptation Case NPV – Base Case NPV.

Table 4.1.5. Estimates of Climate Change Damages, Net Benefits of Adaptation and Residual Damages.

	Base case NPV	Damage case NPV	Adaptation case NPV	Climate Change Damages	Net Benefits of Adaptation	Residual damages
7%	3,673	660	2,204	-3,013	1,544	-1,470
15%	2,625	472	1,553	-2,153	1,081	-1,072

Conclusion and Discussion

The estimates of rainfall data in this study point to increased stress on water availability under climate change, which will adversely affect rice paddy production in Dodoma region of Tanzania. In this case, we demonstrate a simple way of assessing the new benefits of technologies for adaptation. The calculations are based on secondary studies, and the costs and benefits are measured empirically. Scaling up this data, as in the current example, would most likely give a relatively low estimate of the potential climate change damages and benefits from adaptation. Nevertheless, the analysis clearly demonstrates that the returns to the investment in extended water storage capacity under climate change exceed the returns of the baseline situation with no adaptation technologies in place. Hence, the example shows that a relatively simple technology for adaptation, such as rainwater harvesting, is beneficial in terms of economic returns, in addition to other potential benefits which are not included in these calculations, including increased food security in the dry seasons and other positive side-impacts in terms of improved health conditions from decreased malnutrition, is the latter also being a key vulnerability factor in relation to malaria. Finally, it is worth noting that the residual damages are a measure of the net present value of a project without taking into account climate change. While the rainwater harvesting option yields substantial adaptation benefits, it does not return any positive residual benefits. And in this case, only half the damages can be avoided by adaptation.

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Case Study 2. Ecosystem-based Adaptation in the Brazilian Amazon

Background and Objectives

Ecosystem-based adaptation is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people and communities adapt to the negative effects of climate change at the local, national, regional and global levels (UNEP, n.d.; Munang et al., 2013; World Bank, 2009). Protecting natural ecosystems has other social, environmental and economic benefits that contribute to sustainable development. This study presents a stylized case showing how ecosystem-based adaptation measures can help local forest communities adapt to the adverse effects of climate change in the Brazilian Amazon.

Protected areas cover 1.9 million square kilometers of the Brazilian Amazon and contain 54 per cent of the remaining forest and 56 per cent of its forest carbon (Soares-Filho et al., 2010). Some studies have shown that protected areas act as effective barriers to deforestation (Nelson & Chomitz, 2011; Nepstad et al., 2006). The recent expansion of protected areas in the Brazilian Amazon was responsible for an estimated 37 per cent reduction in the region's total deforestation between 2004 and 2006 (Soares-Filho et al., 2010). Nevertheless, in recent decades, frontier expansion located along the so-called "Arc of Deforestation" is now moving beyond this area to new frontiers, such as the southern border of the Amazonas state (May et al., 2011). Two sustainable development reserves (SDR) from the region are used to represent the base case. Projected future deforestation may affect up to 70 per cent of the reserve's forest cover by 2050 (SDS 2009; Soares et al., 2006). The main livelihood activities inside the reserves include smallholder agriculture (cassava, banana and watermelon), as well as fishing. The collection of forest products such as fruits, nuts, bush meat and timber is common, mainly for own use, as is small livestock raising, such as chickens and pigs (SDS et al., 2009, 2010).

In this case, forest conservation is used as the main measure for local communities to adapt to climate change, as forests can be an important safety net for households in times of food shortages and shocks (Angelsen & Wunder, 2003). However, the vulnerability of forests and of local communities to climate change go hand in hand. The vulnerability of forests, and therefore the capacity for the forest to provide for its local inhabitants, will depend on forests' ability to adapt to changing climate. The rapid rate of climate change is making the resulting ability of forests to continue to be a safety questionable (IPCC, 2002; Locatelli et al., 2010; Seppala, 2009). Moreover, small-scale deforestation and fragmentation is the greatest threat to the ability of the Amazon forest to bounce back from the impacts of climate change (IPCC, 2014). As a result, maintaining the integrity of the Amazon ecosystem is a clear strategy designed to help local communities adapt to climate change impacts.

Measures like conservation and restoration of the forest ensure that the forests still provide the provisioning goods and ecosystem services to help support smallholders facing unstable agricultural yields resulting from climate change. The adaptation case is therefore a situation in which forest conservation occurs, thereby preserving or restoring an intact ecosystem. The base case is the "business-as-usual" without climate change, whereby smallholders open up small parcels of land for agriculture and supplement incomes through the extraction of forest products. This case study is real and based upon current incentive schemes for conservation in the Brazilian protected areas; however, the adaptation case has been hypothesised. The assessments of measures are based on residual damages and the net benefits of adaptation.

Methods and Data

In this case, several assumptions on climate change effects are made. First, we assume that precipitation will be reduced, leading to a change in vegetation type to scrubby, open vegetation. Fire frequency will also increase as a result, and with this forest dieback,[41] so that the available forest goods and environmental services will dramatically decrease. These assumptions are made on the basis of the current scientific evidence set out below.

According to the IPCC AR5, there is a high level of confidence that precipitation in the region will decrease due to reduced evapotranspiration. General Circulation Models (GCMs) predict a drying climate affecting soil moisture, which may accelerate the conversion of forests into pasture, and lead to a greater severity and probability of droughts, reinforced by deforestation effects. Occasional severe droughts, exemplified by natural phenomena like El Niño, would kill many trees of susceptible species. The result would be the replacement of tropical moist forest with more drought-tolerant forms of scrubby, open vegetation resembling the *cerrado* (scrub savannah) of central Brazil (Shukla et al., 1990). The risk of burning and fires could also increase, which could affect the nutrient cycling in Amazonian forest ecosystems (medium confidence). The extent to which these nutrient sources could increase the growth of Amazonian forests is not known. Increases in growth differ by tree species and will consequently alter forest composition. Climate, and size and behaviour of the human population, affect the frequency and intensity of burning of the forests. It is critical to keep the factors influencing the growth of intact forests in Amazonia in balance, due to the large amounts of carbon that could be released to or removed from the atmosphere if the balance between forest growth and decay is altered.

Indeed, the ecological services provided by the Amazon, such as evapotranspiration, carbon storage and biodiversity conservation, may be threatened by global warming through to late century (Nepstad et al., 2008). Expanding the global demand for biofuels and grains, and positive feedbacks in the Amazon forest fire regime and drought, may drive a faster process of forest degradation that could lead to a near-term forest dieback. Rising worldwide demands for biofuel and meat are creating powerful new incentives for agro-industrial expansion into Amazon forest regions. Forest fires, drought, and logging increase the susceptibility to further burning, while deforestation and smoke can inhibit rainfall, exacerbating the fire risk. If the sea surface temperature anomalies (such as El Niño episodes) and associated Amazon droughts of the last decade continue into the future, approximately 55 per cent of the forests of the Amazon will be cleared, logged, damaged by drought or burned over the next twenty years, emitting 15–26 giga tonnes of carbon into the atmosphere. According to the UNEP Emissions Gap Report (2016), global GHG emissions in 2014 were 52.7 giga tonnes of carbon equivalent,[42] meaning that the Amazon forests could be contributing annually up to 2 per cent of global emissions, assuming the same growth rates for emissions from Amazon and total global emissions. To avoid a potential tipping point, after which the Amazon will experience forest dieback and not be able to bounce back, human interferences such as burning, clearing for soya and pastures must be reduced. This also highlights the need to extend protected areas closer to the agricultural frontier (Nepstad et al., 2008). Therefore, in this case, we regard forest restoration as an important means of ecosystem-based adaptation in the Brazilian Amazon. For simplicity, we ignore the time lag between conservation efforts and adaptation benefits.

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41 Forest dieback refers to a situation of forest stress where the forest reduction/tree mortality rate is significantly higher than the normal rate of forest reduction/tree mortality. Here we use it in the context of the significant degradation of forests through their replacement by savannah and semi-arid vegetation (Nepstad et al., 2008).

42 http://uneplive.unep.org/media/docs/theme/13/EGR_2015_301115_lores.pdf

For the analysis, we define the base case as the situation with existing land-use policies and current climate. The Damage Case is the situation when the climate changes (in this case adversely) and no efforts are made towards conservation of forests. The Adaptation Case is the situation when the climate changes and efforts are made to conserve the forests. The following Table 4.2.1 presents the costs and benefits of these three scenarios. The data for these calculations come from a mixture of primary and secondary sources, listed in the second-last column of the table. In the base case, the total benefits comprise benefits from the extraction of mainly non-timber forest products, benefits from changes in land use (i.e. converting land to subsistence agriculture) and benefits from eco-system services. In the climate damage case, the significant figures are the costs of degradation, i.e. from dieback, the costs arising out of losses from ecosystem services and the benefits that arise from land use change (i.e. converting land to large-scale agriculture). In the adaptation case, the additional costs for conservation are incorporated along with the opportunity cost of land-use change (to agriculture) and of the benefits from the extraction of forest products. In the following section, BCA is presented with ecosystem-based adaptation measures assessed through residual climate change damages.

Table 4.2.1. Data Used in the Analysis

Scenario	Calculation	Source	Comments
Base case			
Benefit of extraction of forest products USD per ha	32+315 = 347	Using census data, household survey data or other references	Costanza et al., 1997
Benefit of land-use change (e.g. cassava production) USD per ha	255	Household survey data from Börner et al. (2013)	
Benefit of ecosystem services (USD per ha)	1660	Using benefit transfer	Costanza et al., 1997
Climate Damage Case			
Cost of degradation (loss of some forest products) USD per ha	up to 347		As the extent of forest dieback is uncertain, it could mean the loss of up to this amount
Cost of loss of ecosystem services USD per ha	up to 1660		
Benefit derived from land-use change USD per ha	up to 255	Börner et al. (2013)	This assumes land is still productive, but total productivity may not be as high due to the loss of some ecosystem services
Adaptation Case			
Opportunity cost of land use change USD per ha	up to 255	Börner et al. (2013)	Other sources could be: national census vs household surveys, stated preference surveys, revealed preference
Costs of conservation monitoring bring new areas under protection (USD per ha)	0.10-0.20+$0.50 = 0.70 per ha	Nepstad et al. (2008)	Using public forest stewards or government
Benefit of extractive activities	347	Using census data or household survey data or other references	Costanza et al., 1997

Results

Base Case

In calculating the net benefits from the forests, one should ideally consider the multiple benefits that the ecosystem provides under the current climate (that is, without climate change). In this case this would include the value of extracting forest products, plus various ecosystem services, such as watershed protection, biodiversity conservation and carbon sequestration, and the value of land-use. This approach goes beyond the market valuation of derived products and begins to explore contingent valuation techniques.

For the purposes of simplicity, we assume that the net benefits are represented by the income derived from land-use change to small-scale agriculture and income from the extraction of forest products. For this, we have used a recent survey undertaken in the Amazonian reserves that determine the value of the extraction of forest goods, as presented in Table 4.2.1.

To derive a value for ecosystem services, one may opt to implement a preference survey into willingness-to-pay for certain services (e.g. recreation). However, such methods are often criticized for their methodological robustness, which also influences the reliability and validity of estimates (e.g. see Bateman et al., 2002; Whittington 2002). Another option for valuing ecosystem services is through benefit transfer, i.e. by transferring the values derived from studies in other contexts to the context being examined. This offers an alternative to overcome the paucity of studies and data scarcity. This method is also gripped with problems because drawing analogies and capturing context-specific uses of ecosystem services among unique ecosystems is a complex task. To value ecosystem services, we have used benefit transfer using a study done by Costanza et al. (1997).

Similarly, it is possible to incorporate the costs of land use through census data (e.g. agricultural censuses), which often capture the predominant agricultural production systems prevalent in an area. In the inhabited sustainable development reserves in the Amazon, such as Juma and Uatuma, land use can involve clearing for traditional slash-and-burn cultivation of cassava. Cassava tubers are processed on farm into cassava flour, an important national staple. This represents the single most important anthropic land use in our two study areas: over 80 per cent of the survey respondents reported having planted cassava on land cleared between 2008 and 2010. In our survey year, the average size of cropland among forest-dwelling households was 1.8 ha (with a 2.7 standard deviation) per family. However, any percentage of household income can also be derived from the extraction of forest products (Börner et al., 2013).

To sum up, in the base case, we assume that the net benefits are represented by the income from the extraction of forest products, the income derived from small-scale agriculture and the benefits of intact ecosystem services, which to a large degree impact on local climatic conditions (i.e. precipitation) and therefore the productivity of land-use change options. This amounts to US$2262 per hectare in net benefits (Table 4.2.2). It is important to note here that current conditions or "business as usual" are characterized by smallholder agriculture at low population densities, with supplementary incomes from forests. Further, population increases could lead to further land conversion and clearing that would accelerate forest degradation and deforestation, potentially impacting the integrity, and therefore value, of ecosystem services provided. We assumed the benefits p.a. from the extraction of forest products, land-use change and ecosystem services to remain unchanged.

Sensitivity analyses using different discount rates for the base case net present values are shown in Table 4.2.2. These results show that "business as usual" would generally result in a positive NPV over a ten-year period, assuming all things remain the same. However, this scenario is unlikely, as population will increase, leading to more land conversion and deforestation, and likely the partial loss of some ecosystem services.

Table 4.2.2. Base Case Net Present Value (NPV).

	US$	Discounted Net Benefits (NPV) US$			
Year	Net Benefits	5%	10%	15%	20%
1	2,262	2154	2056	1967	1885
2	2,262	2052	1869	1710	1571
3	2,262	1954	1699	1487	1309
4	2,262	1861	1545	1293	1091
5	2,262	1772	1405	1125	909
6	2,262	1688	1277	978	758
7	2,262	1608	1161	850	631
8	2,262	1531	1055	739	526
9	2,262	1458	959	643	438
10	2,262	1389	872	559	365
NPV		**17,467**	**13,899**	**11,352**	**9,483**

Climate Damage Case: Without Adaptation, With Climate Change

The projected climate impacts indicated above (e.g. drying of the Amazonian climate) point to a higher risk of burning, drought and potential dieback of ecosystems as a result of a combination of GHG emissions scenarios and human-induced land-use change.

Costs associated with such a scenario would then include:

- Costs equal to or less than the value of extracted goods
- Costs equal to or less than the value of ecosystem services per hectare

Average costs p.a. under consideration (i.e. cost of degradation and loss of ecosystem services) are assumed to remain unchanged.

Benefits associated with this scenario would include:

- Benefits equal to or less than the current benefits of land-use change, assuming that the irrigation required to support agriculture will be appropriately sourced, as this would now be the primary (and potentially sole) income source for households.

The average benefits p.a. derived from land-use change are assumed to remain unchanged. As noted above, the extent of loss is uncertain, but we have assumed that total loss has occurred. In terms of benefits, we have assumed a continuation in smallholder agriculture in the area, again assuming all things remain the same.

The results of the sensitivity analysis using different discount rates for climate damage NPVs are given in Table 4.2.3. The climate change damage case shows a negative NPV at all discount rates over a ten-year period. The net benefits are negative, resulting from the loss of value of extracted forest goods and the loss of ecosystem services (from Table 4.2.1).

Table 4.2.3. Net Present Value of Climate Damage Case.

	US$			Discounted Net Benefits (NPV) US$			
Year	Benefits	Costs	Net Benefits	5%	10%	15%	20%
1	255	2,007	(1,752)	(1,669)	(1,593)	(1,523)	(1,460)
2	255	2,007	(1,752)	(1,589)	(1,448)	(1,325)	(1,217)
3	255	2,007	(1,752)	(1,513)	(1,316)	(1,152)	(1,014)
4	255	2,007	(1,752)	(1,441)	(1,197)	(1,002)	(845)
5	255	2,007	(1,752)	(1,373)	(1,088)	(871)	(704)
6	255	2,007	(1,752)	(1,307)	(989)	(757)	(587)
7	255	2,007	(1,752)	(1,245)	(899)	(659)	(489)
8	255	2,007	(1,752)	(1,186)	(817)	(573)	(407)
9	255	2,007	(1,752)	(1,129)	(743)	(498)	(340)
10	255	2,007	(1,752)	(1,076)	(675)	(433)	(283)
NPV				**(13,528)**	**(10,765)**	**(8,793)**	**(7,345)**

Adaptation Case: With Adaptation, With Climate Change

The adaptation case is represented by conservation measures that are implemented. For simplicity, we assume that land conversion will stop and that there will be costs associated with conservation, e.g. in monitoring and enforcement, as well as the establishment of protected areas. In summary, the costs associated with adaptation with climate change would be:

- Costs equal to the benefits derived from agriculture (US$255 per hectare). This also represents the "opportunity costs" of land use (in this case assumed to be small-scale agriculture), as the local communities will have to forego land clearing and conversion in order to conserve forests. The costs of conservation (US$0.70 per hectare) come from Nepstad et al. (2008)

Average costs p.a. under consideration (i.e. opportunity costs and conservation costs) are assumed to remain unchanged.

The benefits associated with adaptation to climate change would be:

- Benefits equal to the value of the ecosystem services that are maintained as a result of maintaining an intact ecosystem (up to US$1660 per hectare)
- Benefits equal to the extraction of forest products (up to US$347 per hectare)

The average benefits p.a. of extractive activities are assumed to remain unchanged.

The sensitivity analysis using different discount rates for net present values under the adaptation case are given in Table 4.2.4. With adaptation, the NPV is positive, though not as high as in the base case. This is because we have assumed that land-use change will not occur, this being treated as an "opportunity cost" of the land in the analysis. The costs of land-use change to small scale agriculture assessment are taken from Börner et al. (2013).

Table 4.2.4. Net Present Value (NPV) Adaptation Case.

	US$			Discounted Net Benefits (NPV) US$			
Year	Benefits	Costs	Net Benefits	5%	10%	15%	20%
1	2,007	256	1,752	1,668	1,592	1,523	1,460
2	2,007	256	1,752	1,589	1,448	1,324	1,216
3	2,007	256	1,752	1,513	1,316	1,152	1,014
4	2,007	256	1,752	1,441	1,196	1,001	845
5	2,007	256	1,752	1,372	1,088	871	704
6	2,007	256	1,752	1,307	989	757	587
7	2,007	256	1,752	1,245	899	658	489
8	2,007	256	1,752	1,185	817	573	407
9	2,007	256	1,752	1,129	743	498	339
10	2,007	256	1,752	1,129	743	498	339
NPV				**13,525**	**10,762**	**8,790**	**7,343**

Estimates of Climate Change Damages, Net Benefits of Adaptation and Residual Damages

Under the different discount rates, the estimates of climate change damages, net benefits of adaptation and residual damages are given in Table 4.2.5. These results show that the net benefits of adaptation will neutralise 87% of the climate change damages.

Table 4.2.5. Estimate of Climate Change Damages, Net Benefits of Adaptation and Residual Damages

Discount Rate	Base case NPV US$	Damage case NPV US$	Adaptation case NPV US$	Climate Change Damages US$	Net Benefits of Adaptation US$	Residual Damages US$
5%	17467	(13,528)	13525	(30,995)	27,053	(3,942)
10%	13899	(10,765)	10762	(24,664)	21,527	(3,137)
15%	11352	(8,793)	8790	(20,145)	17,583	(2,562)
20%	9483	(7,345)	7343	(16,829)	14,688	(2,140)

Conclusion and Discussion

This case presents a stylized example of valuing the net benefits of ecosystem-based adaptation. In many cases the data required may be difficult to find, as they often rely on the availability and accessibility of local-level data, as well as data for services that are already very hard to value. The study has relied on other scientific valuation studies of ecosystem services to derive these values, but even these numbers have large degrees of uncertainty. Indeed, the value of ecosystem services will vary widely as a result of different biomes and ecosystems, as well as the wide variety of the users of ecosystem services. As a result, this case has by no means captured the full complexity associated with the evaluation of ecosystem services and ecosystem-based adaptation. Nevertheless, in the simplified case presented above, the results indicate that, across a range of discount rates, the net benefits of ecosystem-based adaptation will remain positive and the climate change damages are likely to be high.

As in the previous RWH example in this chapter, climate change damages are substantially negative. While net adaptation benefits are also substantial, they are not large enough to avoid all of the climate change damages. As a result, there are negative residual damages (costs) that hover around 20 per cent of the Base Case NPV. These residual damages are small – in the range of 13 per cent – relative to the net benefits of adaptation, which avoid around 87 per cent of the climate change damages. However, because eco-system adaptation does not improve upon the Base Case NPV, this is not a no-regrets option, and it might not be competitive compared to other alternative projects funded by the Brazilian government or bi- and multilateral organizations that do not base their analysis on climate accounting.

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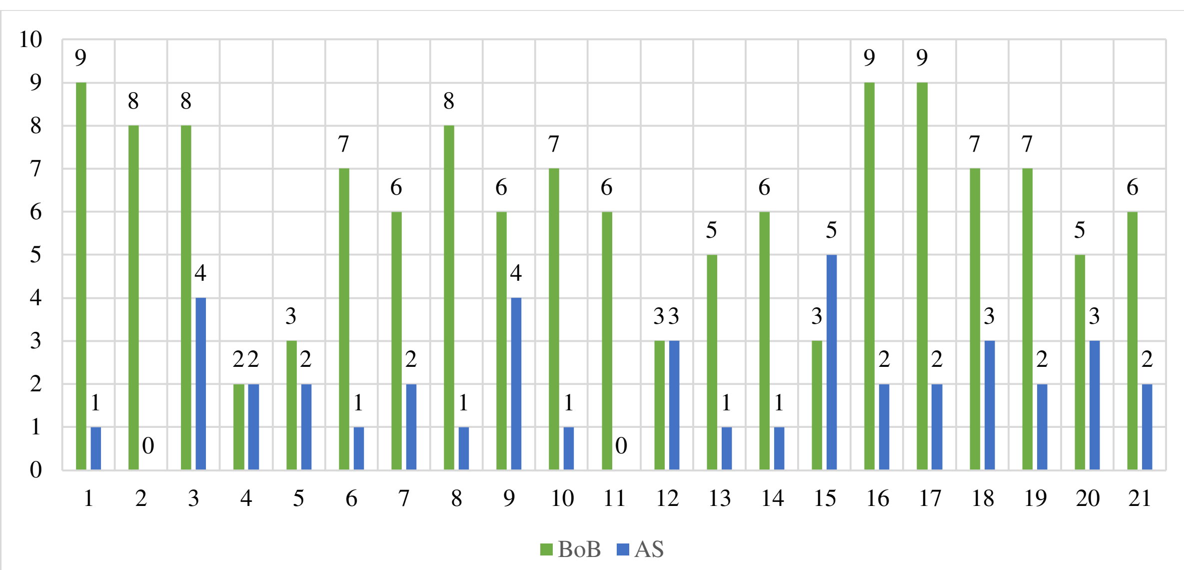
Case Study 3: Reduction of Cyclonic Damage in India

This case study is another simplified example for bottom-up analysis. In the above two cases of rainwater harvesting in Tanzania and ecosystem-based adaptation in the Brazilian Amazon, we looked at one form of intervention in the adaptation case. In general, there would be more than one adaptation alternative relevant for the climate change scenario. In this hypothetical case, which we try to frame around cyclonic disturbances in the Bay of Bengal, we look at the metrics of the net benefits of adaptation and residual climate change damages with two potential adaptation options. One of them is a physical intervention that has high upfront costs and reduces exposure immediately after implementation. The other is a softer intervention that is low in cost but reduces exposure only in the long run. The economic benefits and costs in the assessment reflect private values based on actual financial flows.

Introduction

The Arabian Sea (AS) and Bay of Bengal (BoB) are two seas located in the northern Indian Ocean. Cyclonic disturbances in these seas have disrupted the area's socio-economic systems and caused damage to life, physical infrastructure, flora and fauna. Since 1891 (until 2014), the meteorological department of India has recorded 1186 cyclonic disturbances (including depressions) in the Bay of Bengal, while the same number for the Arabian Sea is 211, which is approximately five times fewer than in the Bay of Bengal. This difference is attributable to differences in temperature in the two seas and other physical factors like salinity, as suggested by many scientists (Balachandran & Geetha, 2014; Evan & Camargo, 2011; Niyas et al., 2009). Figure 4.3.1 shows the twenty-year frequency of cyclonic disturbances in the Arabian Sea and the Bay of Bengal.

Figure 4.3.1 Annual frequency of cyclonic disturbances in the Bay of Bengal (BoB) and the Arabian Sea (AS). Source: Indian Meteorological Department Database.[43]



43 Available at: http://www.rmcchennaieatlas.tn.nic.in/login.aspx?ReturnUrl=%2f

In general, the past is not a good indicator of the future under climate change scenarios. Some studies show that tropical cyclones have intensified during the cyclone months of May, October and November, with November witnessing a 26 per cent increase in the last century (Singh, 2010). Many scenarios also project decreases in the frequency but increases in the intensity of cyclonic disturbances in the northern Indian Ocean (Murakami et al., 2013; Patwardhan et al., 2012).

The coastal districts of the eastern coast of India, such as Srikakulam, Vizianagaram, Visakhapatnam, Guntur and East Godavari, are increasingly becoming centres of economic prominence after the separation of Telangana state from Andhra Pradesh. Visakhapatnam port is one of the major ports of India and the second largest in terms of volume of goods handled per annum (IPA, 2014). Many districts have hubs of economic activities such as the special economic zone in Kakinada, East Godavari, which is a hub for deep-sea and offshore activities in the Krishna-Godavari basin and is a petrochemical investment region. Cyclonic disturbances are a frequent phenomenon in the Bay of Bengal. The prominent ones in the last few years have been Hudhud, Phailin, Nilam, Nargis, Aila etc., which have caused loss of life, damage to infrastructure and disruption of economic activities in the region. The state government of Andhra Pradesh estimated that cyclone HudHud caused damage of 21,908 crore INR, which is approximately 3.37 billion USD (DNA India, 2014). Of this, about a quarter of the damage was to industries and the port infrastructure in Visakhapatnam, though damage to the agriculture sector comprised the maximum share. Similarly the damage caused by cyclone Hudhud were about Rs. 8,000 crore INR (i.e. 1.33 billion USD) in the city of Visakhapatnam in 2014 (Business Standard, 2014).

Climate Risks and Existing Adaptation Measures

The exposure to cyclones on the eastern coast of India is primarily to human life, infrastructure, industry and agriculture. Progress in early warning systems and information dissemination has helped the government achieve remarkable success in preventing the loss of human life. Mass evacuation drives have been made possible by mobile phone communications. The ports and offshore operations have real-time updates on weather phenomena. The guidelines formulated by the cyclone research centre detail the course of action for offshore operations and ports in the event of a specific warning. The storm shelters, coupled with early warning systems, have made it is easier to prevent the loss of life. In the recent past, these adaptive practices have saved many lives, and expanding adaptation actions has the potential for damage prevention (Seo & Bakkensen, 2016). The early warning signs work effectively for offshore platforms, which are shut down once such information becomes available. While these adaptive actions are taken only when the event is about to occur, the scale of proactive measures remains small.

Strong winds and flooding are the immediate consequences of a powerful cyclone. Mangrove plantations are known to inhibit the damage from strong winds and to protect coastal regions from cyclone-induced flooding. The State of Forest Reports[44] from the Forest Survey of India suggest that in many locations mangroves have become stable or changed composition, with more dense mangroves becoming thinner in coastal districts of India. Sea walls and coastal levees are not very common in India.

Understanding the Costs and Benefits of Adaptation

Cyclonic activities are a cause of concern because the existing systems are not equipped to deal with them. There are very limited studies on the changes to cyclonic activity in the Bay of Bengal. The results from projections of the northern Indian Ocean project an increase in the intensity of cyclones in BoB and an

44 Available at: http://fsi.nic.in/

increase in their frequency in AS (Murakami et al., 2013; Patwardhan et al., 2012). In general, the projections for cyclonic activities are not as easy to formulate because of the complex physical phenomenon that lead to cyclone formation.

Protecting coastal infrastructure requires prevention from flooding and protection from strong winds. Taking data limitations into account, let us take a hypothetical example by putting things in the simple context of a town in the region that has seen increased economic activity and is exposed to the threat of cyclonic disturbances. In the following sections, we present a case concerning a hypothetical district. The background information on cyclonic disturbances and the subsequent economic impacts on the eastern coastal districts of India is provided to give a context to readers on the problems posed by cyclonic disturbances. We call this hypothetical district 'A'. Industries like petrochemicals and fertilizers are an important feature of the industrial structure. The district is also a port area, with relatively new infrastructure.

The numbers presented are hypothetical, but have the primary aim of understanding the choice of adaptation practices. Needless to say, making adaptation choices under conditions of climate uncertainty needs a lot more information and tighter assumptions. At every instance when a number is assumed, a set of considerations made in gathering data on the variable are also mentioned. In practice, a number of exogenous variables, too numerous to mention, feed into the projections. In the case of the many exogenous inputs for which we do not have estimates, we assume the numbers and have used secondary sources to bound them.

Flooding in district 'A' can be prevented in two ways, first by building coastal dykes, which also ensures that the city is protected from sea-level rises, and second by having new mangrove plantations spread more widely along the coast. A third option is to have a mixture of both these strategies. Quite often, the choices are not mutually exclusive, and a mixture of all the relevant ones has to be adopted for the adaptation outcome to be resilient.[45]

Exposure Level, Return Period and Future Damage

The present-day damage potential of district 'A' would depend on the intensity of the hazard and the exposure levels of the district. The exposure of district 'A' from cyclonic disturbances is a sum of the following components. For each of these components, one has to consider the economic valuation.

- Physical damages infrastructure/Replacement costs. These would include roads, port infrastructure, residential and commercial structures, etc. These costs not only include the depreciated capital values of the infrastructure, but also should reflect the cost for replacement.
- Damage to economic activities (including man hours lost). Damage to industry and the service and agricultural sectors could be permanent or temporary in nature. This would include the costs of the restoration of normal operations, the loss of man-hours during the precautionary period, and those lost due to sickness as an outcome of cyclonic storms or the subsequent flooding, loss of profits, slowdown in economic activities etc.
- Loss of human life. Economic valuations of human life do not have a standard context in economics. In this specific example, we assume the loss of life as zero. We assume that the civil administration's prompt response to early cyclone warnings leads to no loss of life. Concepts from the statistical value of life can be used if needed to value the loss of life.

45 An alternative, not considered here, is to move the population and infrastructure of the district out of "harm's way". This is not considered a realistic option in the short term.

This economic exposure reflects the potential of loss from the economic activities that are affected by cyclones in the coastal district. The past incidents of cyclone-induced damages are only indicative of the extent of exposure. Often the damage estimates account only for the monetary value of damage to physical infrastructure. They could also include the damages due to loss of economic activities and the cost of replacements. Let us assume that the economic exposure level of district 'A' is 1.5 billion USD in 2015 in real monetary values, which includes the infrastructure damage potential and losses due to the halt in economic activities. The increase in the economic exposure rate is assumed to be in the range of 7 to 12 per cent (Table 4.3.1). These exposure levels will increase based on increases in economic activity, the concentration of physical infrastructure etc. Since district 'A' is a growing district, it will witness an increase in activities in the next few years, following which growth will stabilize and then decline. Table 4.3.1 shows the growth rate in exposure. Annual values for exposure levels are given in the technical annexes at the end of this chapter (Annex 1). Choosing an appropriate discount rate will entail other sets of considerations as mentioned in the introduction to this chapter.

Table 4.3.1. Increase in Economic Exposure to Cyclones in District A.

Year	Increase in economic exposure
2016-2025	10%
2026-2035	12%
2036-2045	9%
2046-2050	7%

From historical data sets, we have frequencies of cyclonic disturbances based on intensities. Of the 1186 cyclonic disturbances in the last 120 years, 680 were depressions (D) or deep depressions (DD), 279 were cyclonic storms (CS), and 227 were severe cyclonic storms (SCS), very severe cyclonic storms (VSCS) or super cyclones (SuCS). Let us assume that only super cyclones are potentially damaging to the economic activities in district 'A'. We have the current return period for various categories of cyclone. Let us assume, from the existing return period, that the return period for super cyclones is reduced to 2.5 and 2 for the periods 2015-2025 and 2026-2050 respectively. Research and secondary literature with projections for increases in the frequency of cyclonic disturbances can constitute an input to determine the return period.

Table 4.3.2. Frequencies of Cyclonic Disturbances and Return Period of Super Cyclones.

Year	Frequency of all cyclonic disturbances p.a.	Increase in total SuCS frequency w.r.t 2015	Frequency of SuCS p.a.	Return period
2015	10		0.33	3
2015-2025	12	20%	0.40	2.5
2026-2050	14	50%	0.50	2

Before moving to the different cases with and without adaptation options, we define the economic metrics that are used here to assess the various options. Damages due to climate change is defined as losses (positive or negative i.e. improvements) in welfare (socio-economic) of the society due to the increased frequency and intensity of climate change variables like temperature, sea-level rise, precipitation etc., where only existing interventions of technology, infrastructure or economics can be used to avoid climate change impacts (or enhance the benefits of improvements). Welfare calculations are based on a private-market perspective, which is more empirical and follows financial flows (or imputed shadow prices).

The net adaptation benefits are defined as the avoided climate change damages due to adaptation intervention. In this case, these benefits include the prevention of losses from cyclonic flooding that could potentially damage the industrial, economic and household sectors of district 'A'. The adaptation options are building coastal dykes (option 1), developing mangroves in coastal zones (option 2) and a mixed strategy of the two (option 3).

The costs of adaptation are the monetary values of the resources used to implement the intervention. They could be capital or variable. Capital costs are defined as the upfront implementation costs for the intervention. They are usually one-off investments to make the intervention working. In this case, it could be the capital cost of building sea walls, including labour costs, technical and planning costs, and material costs, to make the interventional functional. Variable costs are regular costs that have to be incurred in order to maintain the expected output levels. In the case of sea walls, variable costs would include regular repair and maintenance to keep up their strength. In the case of mangrove plantations, this would include the maintenance of freshwater channels, adding nutrients, and checking for diseases etc.

The net adaptation benefits, therefore, are the difference between these two values, i.e. adaptation benefits less adaptation costs. Even after implementing adaptation alternatives, there is a possibility of loss. These residual damages or losses are defined are the losses in welfare after taking into account the adaptation interventions. If the adaptation options more than eliminate the climate change damages, then there will be residual benefits. In the damage and adaptation cases below, we assume the values of costs, benefits, economic exposure and potential damage as an outcome of the increased frequency of super cyclones. The technical annexes present more details on these values.

The Damage Case: Option 0 (Do Nothing)

The damage case is when the climate changes and no special effort is made to adapt. The economic exposure of district 'A' is quantified in Annex 1. The actual damage will depend on the interplay between exposure and hazard. The exposure to a super cyclone translates into 5 per cent of losses based on economic exposure until 2040, after which the loss percentage increases to 10 per cent (Table 4.3.3). Since the return period changes, this damage will not occur every year.

Table 4.3.3. Expected Per cent Economic Losses from Cyclones in District A.

	Expected Damage (Per cent Losses)
2016-2040	5%
2041-2050	10%

Damage = Economic exposure * damage potential of super cyclone ***Equation 4.3.1***

Total Cumulative Economic Damage = 6.664 billion USD (nominal)

This forms the damage case of doing nothing when the climate changes, i.e. the case of W(C1,A0) as described in the section on money metrics for adaptation (Chapter 2). In the following sections, we now examine the effects on the damages if adaptation measures are implemented.

Avoided Damages with Adaptation Options

The adaptation case involves the introduction of an adaptation option in a changed climate situation, i.e. the case of W(C1,A1) as described in the section on money metrics for adaptation (Chapter 2). In this section, we discuss the avoided damages with adaptation options. The options under consideration are building coastal dykes (option 1), developing mangroves in coastal zones (option 2) and a mixture of the two (option 3). Each of these options differs in terms of the investment requirements, the maintenance costs and the time frame to yield results in the form of coastal protection and the strength of protection.

Building coastal dykes is a capital-intensive adaptation alternative. There is a capital cost involved in building them, and they will subsequently require some maintenance costs, which will comprise the variable costs. These are presented in Table 4.3.4. The avoided damage is the percentage of economic exposure that is prevented from damage in the event of a super cyclone when the adaptation alternative is implemented.

Table 4.3.4. Damage Case: Capital and Variable Cost Exposure to Cyclones and Damages Avoided 2016-2050 in District A

	Capital Cost	Variable Cost p.a.	Damage Avoided
	10^6 US Dollars (millions)		
2016-2020	500	2	100%
2021-2025		2	100%
2026-2030	100	5	80%
2031-2035		5	75%
2036-2040		5	60%
2041-2045	300	15	70%
2046-2050		15	65%

The annual values of these figures are given in annex 2 (technical annexes at the end of Chapter 4). Tables 4.3.5 and 4.3.6 present the future value (not discounted) of avoided damages for adaptation options 2 and 3.

Table 4.3.5. Future Value of Avoided Damages with Adaptation Option 2 (Mangrove Plantations).

	Capital Cost	Variable Cost p.a.	Damage Avoided
	10^6 US Dollars (millions)		
2016-2020	100	5	30%
2021-2025		5	30%
2026-2030	100	4	40%
2031-2035		4	40%
2036-2040	100	1.5	55%
2041-2045		1.5	55%
2046-2050	100	0.5	65%

Table 4.3.6. Future Value of Avoided Damages with Adaptation Option 3 (Sea Walls and Mangrove Plantations).

	Capital Cost	Variable Cost p.a.	Damage Avoided
	10^6 US Dollars (millions)		
2016-2020	600	7	100%
2021-2025		7	100%
2026-2030	150	9	100%
2031-2035		9	100%
2036-2040	100	1.67	85%
2041-2045	150	3	85%
2046-2050	100	3	85%

It is also important to understand how sensitive the various economic metrics used in an adaptation analysis are to different discount rates. With respect to the latter, there is again uncertainty and disagreement in their appropriate values. The values of future benefits and damages today has not only has economic considerations, but also ethical and other non-quantitative ones. The basis of the discount rate, whether it should be opportunity costs, market interest rates or "something else", based on social rates of time preference is also a subject of much debate, especially when it comes to climate change.[46] Disagreements occur over the value of the discount rate and even on whether it should be high or low. Climate change is a global phenomenon, with impacts spanning across generations and geographies, and is not necessarily suffered by those causing it. Therefore, the rates will be very different, depending on two different arguments: either that future generations will be better equipped and more technologically advanced to deal with climate change, or conversely that those who will be worst affected by adverse events in future will be the poor and marginalized who have not benefitted from increased incomes. Amidst these considerations, we present assumed discount rates. Tables 4.3.7 to 4.3.9 summarize the present values for the adaptation analysis for interest rates of 5, 10, and 15 per cent respectively.

Table 4.3.7. Net Present Values of Economic Metrics in the Adaptation Analysis for the Three Adaptation Options for a 5 per cent Rate of Discount.

Metric	Option 0	Option 1	Option 2	Option 3
	10^6 US Dollars (millions)			
Fixed Costs	0	826.04	354.60	760.35
Variable Costs	0	83.58	60.56	106.28
Climate Change Damages	3,807.50	3,807.50	3,807.50	3,807.50
Damage Avoided (Net Benefits of Adaptation and % of Climate Change Damages Avoided)	0	1,567.48 (41.17%)	1,015.42 (26.67%)	1,890.84 (49.66%)
Residual Climate Change Damage	3,807.50	2,240.01	2,792.07	1,916.66

46 On the subject of climate change, see Arrow et al. (2013); Gollier (2008 and 2015); Quiggen (2008); Stern (2006).

Table 4.3.8: Net Present Values of Economic Metrics in the Adaptation Analysis of the Three Adaptation Options for a 10 per cent Rate of Discount

Metric	Option 0	Option 1	Option 2	Option 3
	10^6 US Dollars (millions)			
Fixed Costs	0	762.58	316.99	629.86
Variable cost	0	37.00	40.85	66.97
Climate Change Damages	2,328.22	2,328.22	2,328.22	2,328.22
Damage Avoided (Net Benefits of Adaptation and % of Climate Change Damages Avoided)	0	680.95 (29.25%)	361.28 (15.52%)	788.10 (33.85%)
Residual Climate Change Damages	2,328.22	1,647.27	1,966.94	1,540.12

Table 4.3.9. Net Present Values of Economic Metrics in the Adaptation Analysis of the Three Adaptation Options for a 15 per cent Rate of Discount.

Metric	Option 0	Option 1	Option 2	Option 3
	10^6 US Dollars (millions)			
Fixed Costs	0	707.65	285.50	564.77
Variable Costs	0	20.48	30.12	47.10
Climate Change Damages	1,523.55	1,523.55	1,523.55	1,523.55
Damage Avoided (Net Benefits of Adaptation and % of Climate Change Damages Avoided)	0	373.41 (24.51%)	164.41 (10.77%)	414.92 (27.23%)
Residual Climate Change Damages	1,523.55	1,150.14	1,359.14	1,108.63

Conclusion and Discussion

Tables 4.3.7 to 4.3.9 show, first, that climate change damages, net benefits of adaptation and residual damages decrease as the discount rate increases, as expected. Second, if we focus on the net benefits of adaptation as the economic criteria for selecting the most economically efficient adaptation measure, the mixed strategy, i.e. option 3, wins out over the other two at all discount rates. This option (3) strategy, combines the sustainable intervention of mangroves, which protect even in the long term, with coastal dykes, which have the potential for immediate benefits.

Using a private-market perspective in a BCA can serve as a starting point. In adaptation assessments, a social perspective of external effects also has to be included. A common practice is to monetize some of these effects. In some events contingent valuation may be used, which measures contingent preferences. The ultimate choice in practice may consider the costs over time, the resources available (financial, technological and capacity) and the co-benefits, among other things. We compared the adaptation options and finally came to a conclusion that a combination of the two options will be the best strategy for district ‘A’. The social perspective will also value other aspects, like the capital investments and the wider benefits for society. It could be possible that district ‘A’ prefers the adaptation option of mangrove channels because it gives more employment to people. Alternatively, district ‘A’ may not have adequate financial support to implement option 3, i.e. the mixed strategy, which requires the greatest amount of capital expenditure.

Establishing an optimal strategy while taking into account the preferences of the society is not an easy task. In practice, putting the trade-offs in front of all stakeholders and letting them decide the best alternative for adaptation may work well. In addition, there are practical problems in even identifying adaptation options and subsequently identifying a smaller consideration pool from them. This smaller subset may have more than three adaptation options and their combinations, thereby making the exercise of BCA very extensive.

In this case, we have attempted to frame an example around coastal Andhra Pradesh to demonstrate the choice between three different adaptation strategies. These concepts are also relevant for cyclone-prone areas in coastal districts, or for similar climate-induced disasters like flooding. In this hypothetical case, we have tried to assume values by bounding them wherever possible with secondary sources. Local consultants and experts have a better understanding of framing the metrics in bottom-up BCA assessments and can bound the assumptions wherever needed. They can also provide better perspectives for determining economic exposure in a particular region. Historical data on climate variables are not necessarily relevant, as historical trends change. In the end, making plausible assumptions to fill the data gaps and define the boundaries of assessment is important.

Technical Annexes

Annex 1 presents detailed information about exposure levels and expected damage in District A. Annexes 2, 3 and 4 present the information used to construct the economic results for adaptation options 1, 2 and 3.

Annex 1. Exposure Levels and Expected Damages in million USD

	Economic Exposure	Expected Damage in case of SuCS
2015	1,500.00	
2016	1,650.00	
2017	1,815.00	
2018	1,996.50	99.83
2019	2,196.15	
2020	2,415.77	120.79
2021	2,657.34	
2022	2,923.08	
2023	3,215.38	160.77
2024	3,536.92	
2025	3,890.61	194.53
2026	3,891.73	
2027	3,892.85	194.64
2028	3,893.97	
2029	3,895.09	194.75
2030	3,896.21	
2031	3,897.33	194.87
2032	3,898.45	
2033	3,899.57	194.98
2034	3,900.69	
2035	3,901.81	195.09
2036	4,252.98	
2037	4,635.74	231.79
2038	5,052.96	
2039	5,507.73	275.39
2040	6,003.42	
2041	6,543.73	654.37
2042	7,132.67	
2043	7,774.61	777.46
2044	8,474.32	
2045	9,237.01	923.70
2046	9,883.60	
2047	10,575.46	1,057.55
2048	11,315.74	
2049	12,107.84	1,210.78
2050	12,955.39	

Annex 2. Option 1, Building Sea Walls (Costs and Damages Avoided in million USD)

	In SuCS	Sea Walls		Damage Avoided	Residual Damage
	Expected Damage	VC	FC		
2016			500	-	-
2017		2.00		-	-
2018	99.83	2.00		99.83	-
2019		2.00		-	-
2020	120.79	2.00		120.79	-
2021		2.00		-	-
2022		2.00		-	-
2023	160.77	2.00		160.77	-
2024		2.00		-	-
2025	194.53	2.00		194.53	-
2026		5.00	100	-	-
2027	194.64	5.00		155.71	38.93
2028		5.00		-	-
2029	194.75	5.00		155.80	38.95
2030		5.00		-	-
2031	194.87	5.00		146.15	48.72
2032		5.00		-	-
2033	194.98	5.00		146.23	48.74
2034		5.00		-	-
2035	195.09	5.00		146.32	48.77
2036		5.00		-	-
2037	231.79	5.00		139.07	92.71
2038		5.00		-	-
2039	275.39	5.00		165.23	110.15
2040		5.00		-	-
2041	654.37	15.00	300.00	458.06	196.31
2042		15.00		-	-
2043	777.46	15.00		544.22	233.24
2044		15.00		-	-
2045	923.70	15.00		646.59	277.11
2046		15.00		-	-
2047	1,057.55	15.00		687.40	370.14
2048		15.00		-	-
2049	1,210.78	15.00		787.01	423.77
2050		15.00		-	-
NPV					
Nominal	6,681.28	243.00	900.00	4,753.73	1,927.56
5%	3,807.50	83.58	826.04	1,567.48	2,240.01
10%	2,328.22	37.00	762.58	680.95	1,647.27
15%	1,523.55	20.48	707.65	373.41	1,150.14

Annex 3. Option 2, Mangrove Channels (Costs and Damages Avoided in million USD)

	In SuCS	Sea Walls		Damage Avoided	Residual Damage
	Expected Damage	VC	FC		
2016			100.00	-	-
2017		5.00		-	-
2018	99.83	5.00		29.95	69.88
2019		5.00		-	-
2020	120.79	5.00		36.24	84.55
2021		5.00		-	-
2022		5.00		-	-
2023	160.77	5.00		48.23	112.54
2024		5.00		-	-
2025	194.53	5.00		58.36	136.17
2026		4.00	100.00	-	-
2027	194.64	4.00		77.86	116.79
2028		4.00		-	-
2029	194.75	4.00		77.90	116.85
2030		4.00		-	-
2031	194.87	4.00		77.95	116.92
2032		4.00		-	-
2033	194.98	4.00		77.99	116.99
2034		4.00		-	-
2035	195.09	4.00		78.04	117.05
2036		1.50	100.00	-	-
2037	231.79	1.50		127.48	104.30
2038		1.50		-	-
2039	275.39	1.50		151.46	123.92
2040		1.50		-	-
2041	654.37	1.50		359.91	294.47
2042		1.50		-	-
2043	777.46	1.50		427.60	349.86
2044		1.50		-	-
2045	923.70	1.50		508.04	415.67
2046		0.50	100	-	-
2047	1,057.55	0.50		687.40	370.14
2048		0.50		-	-
2049	1,210.78	0.50		787.01	423.77
2050		0.50		-	-
NPV					
Nominal	6,681.28	102.50	400.00	3,611.41	3,069.87
5%	3,807.50	60.56	354.60	1,015.42	2,792.07
10%	2,328.22	40.85	316.99	361.28	1,966.94
15%	1,523.55	30.12	285.50	164.41	1,359.14

Annex 4. Option 3, Mixed Strategy (Costs and Damages Avoided in million USD)

	In SuCS	Sea Walls		Damage Avoided	Residual Damage
	Expected Damage	VC	FC		
2016		7.00	600.00	-	-
2017		7.00	-	-	-
2018	99.83	7.00	-	99.83	-
2019		7.00	-	-	-
2020	120.79	7.00	-	120.79	-
2021		7.00	-	-	-
2022		7.00	-	-	-
2023	160.77	7.00	-	160.77	-
2024		7.00	-	-	-
2025	194.53	7.00	-	194.53	-
2026		9.00	150.00	-	-
2027	194.64	9.00	-	194.64	-
2028		9.00	-	-	-
2029	194.75	9.00	-	194.75	-
2030		9.00	-	-	-
2031	194.87	9.00	-	194.87	-
2032		9.00	-	-	-
2033	194.98	9.00	-	194.98	-
2034		9.00	-	-	-
2035	195.09	9.00	-	195.09	-
2036		1.67	100.00	-	-
2037	231.79	1.67	-	197.02	34.77
2038		1.67	-	-	-
2039	275.39	1.67	-	234.08	41.31
2040		1.67	-	-	-
2041	654.37	3.00	150.00	556.22	98.16
2042		3.00	-	-	-
2043	777.46	3.00	-	660.84	116.62
2044		3.00	-	-	-
2045	923.70	3.00		785.15	138.56
2046		3.00	100.00	-	-
2047	1,057.55	3.00	-	898.91	158.63
2048		3.00	-	-	-
2049	1,210.78	3.00	-	1,029.17	181.62
2050		3.00	-	-	-
NPV					
Nominal	6,681.28	198.33	1,100.00	5,911.63	769.66
5%	3,807.50	106.28	760.35	1,890.84	1,916.66
10%	2,328.22	66.97	629.86	788.10	1,540.12
15%	1,523.55	47.10	564.77	414.92	1,108.63

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Case Study 4. Adaptation Benefit-Cost Analysis of Beach Nourishment in a Hypothetical Developing Country Setting

The main objective of this study is to present an example of a more complex adaptation BCA for a beach nourishment program. There are few studies with sufficient information that combine all of the information required to do this at the project or program level. Moreover, the few that were found did not fit together well enough in regional or methodological terms to duplicate this kind of short-cut analysis, as was found for the previous examples in this chapter. For that reason, it was decided to put together a hypothetical case study of how one would approach this task in an actual location, using a spreadsheet analysis to conduct the economic part of the example.

This example assumes that there is a group of adjacent luxury hotels located on beachfront property in a developing country. Over the period from 1990 to 2010, all of the hotels have kept records of the number of bed nights, the expenditure of the hotel residents in their shops, and most importantly, the condition of their tourist-friendly, sandy beaches. The beaches have always been subject to erosion by infrequent storms and on-shore erosion. However, this reduction in beach area volume has been moderated by beach nourishment, which was stopped after a nourishment in the late 1980s, and the beach has deteriorated in quality ever since. Prior to 1990, the nourishment cycles were quite long in duration due to the pre-existing low frequency and duration of storms and the low force of pre-existing on-shore currents running almost parallel to the beach. However, in very recent years, the frequency and duration of intense storms has increased, as has the velocity of on-shore currents. At the same time, the hotel owners have become familiar with several recent studies that have pointed to local sea-level rises, all of which have, or could, create much faster beach erosion. As this has happened in the recent past, bookings, bed nights and beach area volumes have fallen, and along with these, hotel revenues from guest expenditure during their stays. The owners need to attract funding to restore beach quality from private investors, and possibly from multi- and bilateral donors supporting adaptation measures.

The example presented here, of a beach nourishment program, takes as its point of departure assessment of the impact of these geo-physical changes in order to determine the extent to which a revamped long-term beach nourishment program can help the hotels cope with an apparently changed “state of nature”, restore the sandy beaches to their originally attractive state and increase their net long-run profits. The example shows how a hypothetical adaptation BCA would inform the economic hopes of the owners and residents of nearby towns, whose livelihoods rely on increasing tourist visits and expenditure.

Methods

Table 4.4.1 presents the basic data that defines the context for this study.

Table 4.4.1. Hotel and Beach Area and Volume Information for the Example.

Site Characteristic	Measure
Number of hotels	5
Average number of rooms	120
Total rooms	600
Average bed night/room	2.0
Maximum bed nights at average of two guests/room	432,000
Average capacity	372,300 (85%)
Tourist in-hotel revenue per bed night in USD	200
Operating cost/bed night at average capacity in USD	80
Capital investment carried on loan in USD	400,000,000
Annual loan service on capital investment in USD p.a.	
5%	26,021,000
8%	35,531,000
10%	42,432,000
15%	60,920,000
Total beach length	1 Km.
Average beach width	80 m.
Beach fill per unit area	10 m^3/m.
Peak beach volume	800,000 m^3

Hypothetical data sets were created for mean beach area volume/year and bed nights per year for the observation period, 1990-2010 (Figure 4.4.1). The Base Case beach condition was assumed to degrade as it had during the period of hypothetical observation, based on a regression between beach area and years (Figure 4.4.1). Bed Nights, guest expenditure in the hotels and long-run profits for both the Base Case period (2011-2075) and for the climate change/replenishment period (with and without beach nourishment) were simulated using two additional regression relationships (Figures 4.4.2 and 4.4.3) from the period of hypothetical observations, between beach area under 300 $10^3 m^3$ and another for beach area over 300 $10^3 m^3$. Two regressions were estimated because the hypothetical data showed that bed nights were not very sensitive to beach area above 300 $10^3 m^3$ (Figure 4.4.4), but became more sensitive below that value (Figure 4.4.3). These relationships, between beach area and bed nights, were assumed to be based on guest preferences over a wide range of beach conditions such as existed in the data base, from a beach area volume of 650 $10^3 m^3$ down to around 170 $10^3 m^3$. While beach area was dependent on climate change and beach nourishment, guest preferences were assumed to be invariant to the source of beach degradation.

Table 4.4.2 presents the assumptions for the hypothetical beach nourishment simulations.

Table 4.4.2. Assumptions for the Beach Nourishment Case.

Causes of action:	Continual beach erosion from onshore currents, accelerated by sea-level rise and observed frequency of more intensive storms
Simulated erosion rate of beach area volume under existing climate (C0) and climate change (C1)	exp(-.066) for C(0) exp(-.086) for C(1)
Nourishment objective	Repeated nourishment at 300,000 m^3 level up to level of 700,000 m^3, allowing nourishment cycle to decrease in length of time.*
Nourishment cost/cycle	$40/cubic meter of dredged material from offshore
Beach maintenance cost	$600,000/yr.

** The nourishment bounds indicate a region in which bed nights were not very responsive to changes in beach area. See Figures 4.4.1, 4.4.2 and 4.4.3.*

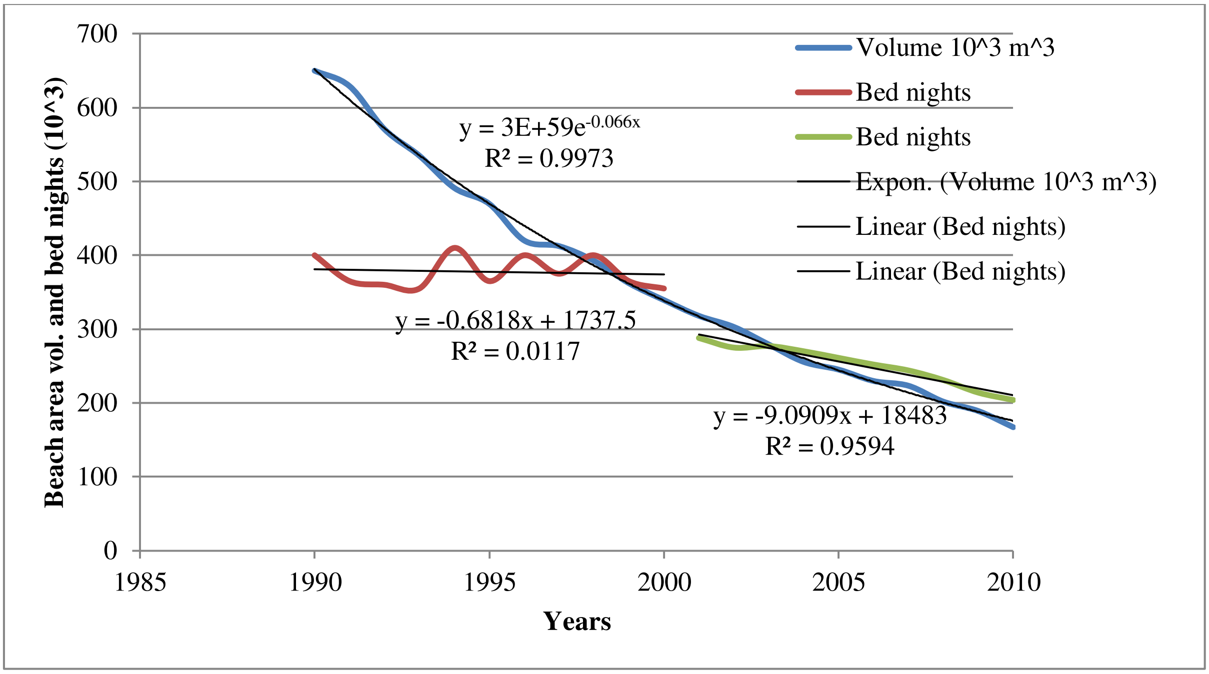
For the climate change case (2011-2075), it is assumed that beach area would degrade at an exponential rate, .02/year per cent, faster than it had in the base case. Only one climate change scenario is used, but it would of course be advisable to perform a sensitivity analysis on this parameter in a more thorough analysis, as the standard errors on the tail observations of extreme values are extremely large. The increased rate of beach degradation was also integrated into the calculations for the beach nourishment cycle. An important assumption made for these calculations was that there are two aspects to the erosion of a nourished beach to maintain beach quality: more material could be added over time at each nourishment to maintain a constant length of each nourishment cycle, or adding the same amount of material in each nourishment could maintain beach quality, though the cycles would become shorter over time to cover the deficit. Both methods were tested to achieve a result that ended in the greatest net benefits to hotel owners. Based on this analysis, the latter approach was selected.[47] Such an analysis, had it actually been performed with a geophysical model of beach erosion and re-nourishment, would produce calculations of the timing, duration and amount of material that needed to be dredged and applied to the beach area, and the resulting beach area under the forces of erosion, increased storminess and climate change over time. Recent descriptions and discussions of the models needed to do this can be found in Karambas and Samaras (2014), Jin et al. (2013), Hinkle et al. (2013) and Nam et al. (2009). However, the beach area profiles shown in this example are hypothetical, based on figures in Harlow and Cooper (1996) for Bournemouth Beach.[48]

Figure 4.4.1 shows the observed hypothetical beach area volume (blue) and bed nights (red and green), as observed from 1984 to 2010. The beach area data were characterized by a downward linear trend at an exponential rate of -.066/yr. The bed-night data from 1990 to 2000 (in red) showed no significant time trend and little observed co-variation with beach area volume, suggesting that bed nights were influenced by other factors than beach volume. However, the hypothetical bed-night data for 2002 to 2010 (green) were characterized by a significant, downward linear trend over time of about -9.09/yr., suggesting that, below a threshold beach area volume of 300 $10^3 m^3$, there was a strong relationship between the beach condition and bed nights.

47 This also resulted in the selection of the duration of the long-term nourishment period, 2011-2075.

48 Additional information was drawn from a Messina Project document, "A case study documenting monitoring and modelling techniques used at Bournemouth, UK: local-specific approach to coastal monitoring" (Isle of Wight Council, 2005): http://ec.europa.eu/ourcoast/download.cfm?fileID=859.

Figure 4.4.1. Beach Area Volume and Bed Nights by Year, 1990-2010.



Figures 4.4.2 and 4.4.3 take a closer look at the relationship in these two groups of bed nights between beach condition and bed nights. Figure 4.4.2 shows a significant positive linear relationship between these two variables below the 300 $10^3 m^3$ beach area volume threshold, but no significant relationship above the threshold (Figure 4.4.3).

Figure 4.4.2. Regression: Bed Nights vs. Beach Area Volume (under 300 $10^3 m^3$).

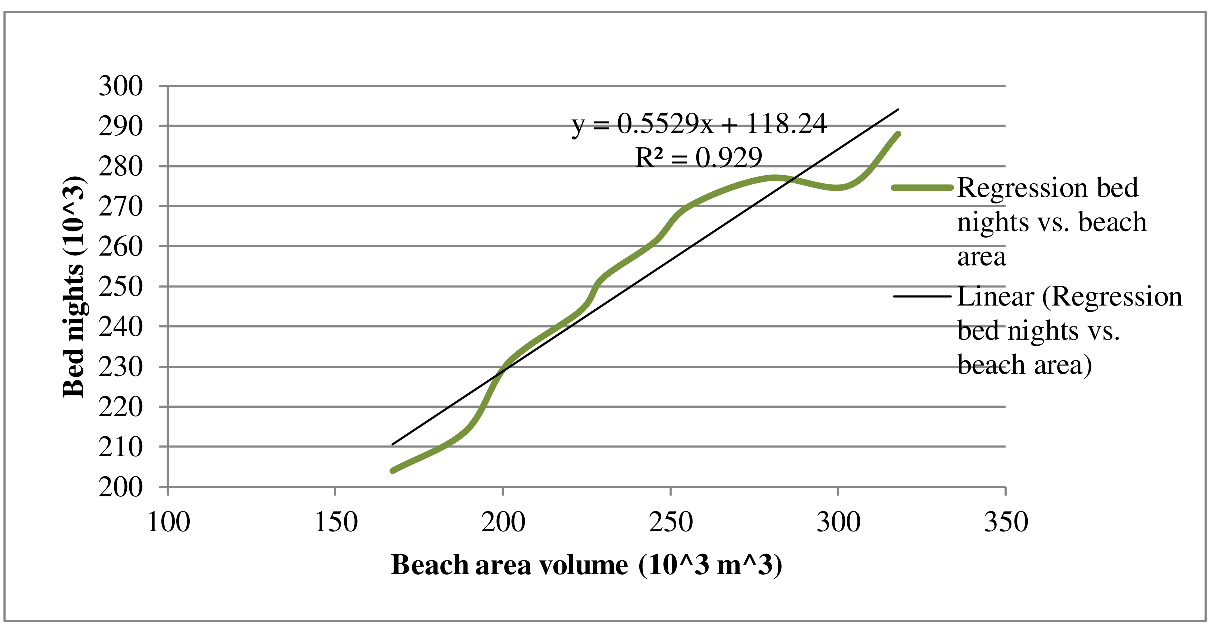
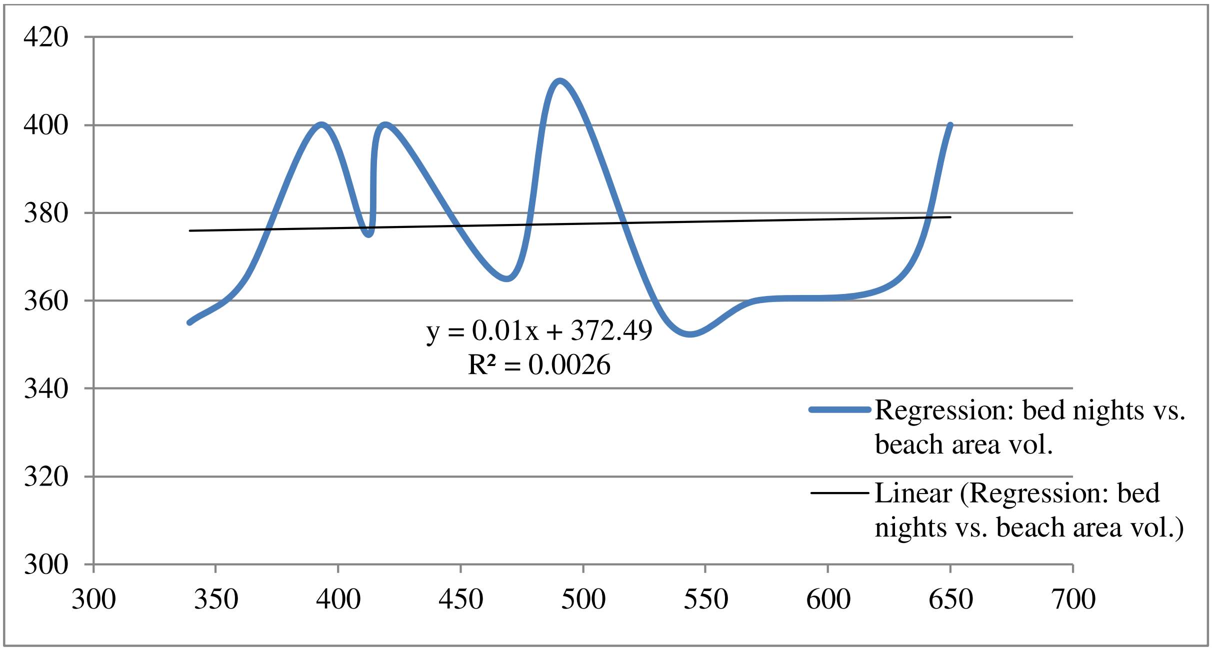


Figure 4.4.3. Regression: Bed Nights vs. Beach Area Volume (over 300 $10^3 m^3$).



Long-term (discounted) net benefits to hotel owners were calculated for the Base Case (no climate change, no beach nourishment), for a climate change damage scenario (climate change, no nourishment) and an adaptation scenario (climate change, plus beach nourishment). Four discount rates were used: 5, 8, 10, and 15 per cent, to reflect the potentially wide range in the opportunity costs of capital. These estimates were used to estimate climate change damages and net benefits of adaptation and to conduct a traditional BCA to determine if the nourishment option was economically feasible in its own right.

Results

The projected impacts of climate change on beach area, without beach nourishment (Figure 4.4.4), are shown in blue (C0) and red (C1) for the period 2010-2070 at the bottom of this figure. The Projected bed-night responses under the two climate scenarios are shown in green (C0) and purple (C1) in the top part of the figure. The annual difference within each of the two sets of curves shows the impact of climate change. The fact that the time-traces for the two variables tend to converge in both climate cases is due to the exponential function for beach volume in Figure 4.4.1.

Figure 4.4.4. Projected Effects of Climate Change (C1) compared to No Climate Change (C0) on Beach Area Volume and Bed Nights by year, Without Adaptation (2010-2070).

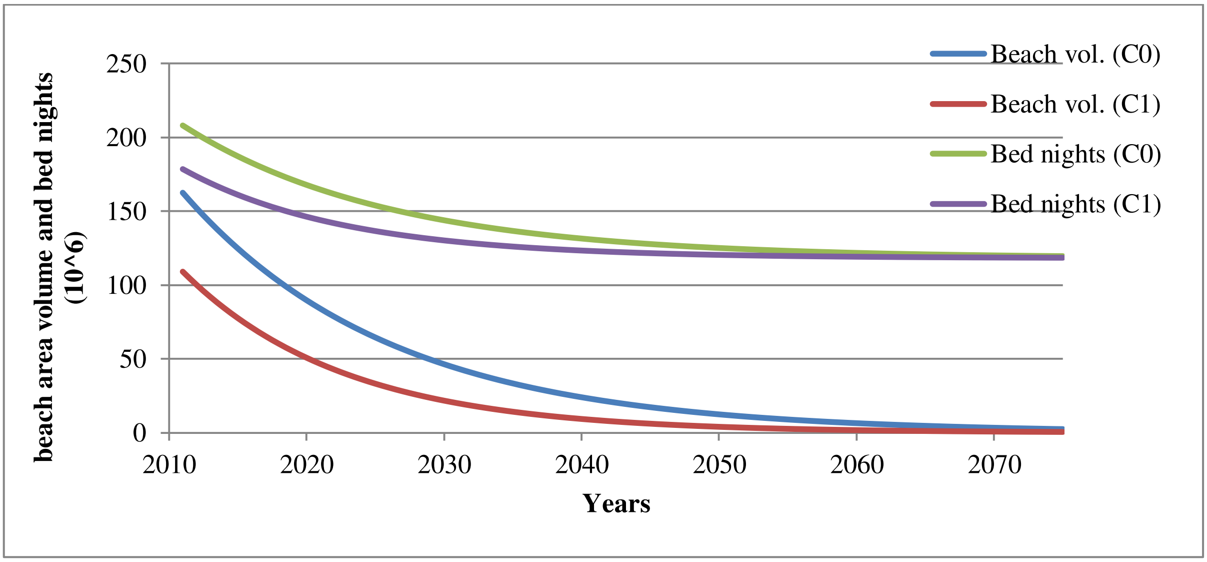


Figure 4.4.5 illustrates the effects of simulated beach nourishment from the hypothetical geo-physical erosion modelling exercise on beach area volume, due to the addition of the same level of beach fill in each nourishment cycle, patterned after Harlow and Cooper (1996). The effects of climate change on beach area volume are shown by the decreasing lengths of the duration of the three nourishment cycles: 25 years in the first cycle, 20 years in the second cycle, and 15 years in the third cycle. As such, the differences over time in bed nights, with and without climate change, represent the physical analogue of climate change damages.

Figure 4.4.6 shows the projected effects of beach nourishment on bed nights under the climate change scenario. Projected beach nights, with nourishment, shown in red at the top of the picture are flat compared to the shapes of the nourishment cycles. This is simply due to the fact that bed nights were not significantly correlated with beach area (Figure 4.4.3) over the level of 300 10^3m^3 in the hypothetical observed data set. Projected bed nights without beach nourishment (Blue), on the other hand, were correlated with beach area volume below this threshold, (Figure 4.4.2), which is reflected in the later period[49] in the downward, and then almost flat projected trend.

49 The five-year, delayed response of bed nights to beach area volume is related to the time delay in building up the initial replenishment level from a very low level to 300 10^3m^3.

Figure 4.4.5. Projected and Fitted (Moving Average-2) Beach Are Volume for Three Nourishment Cycles.

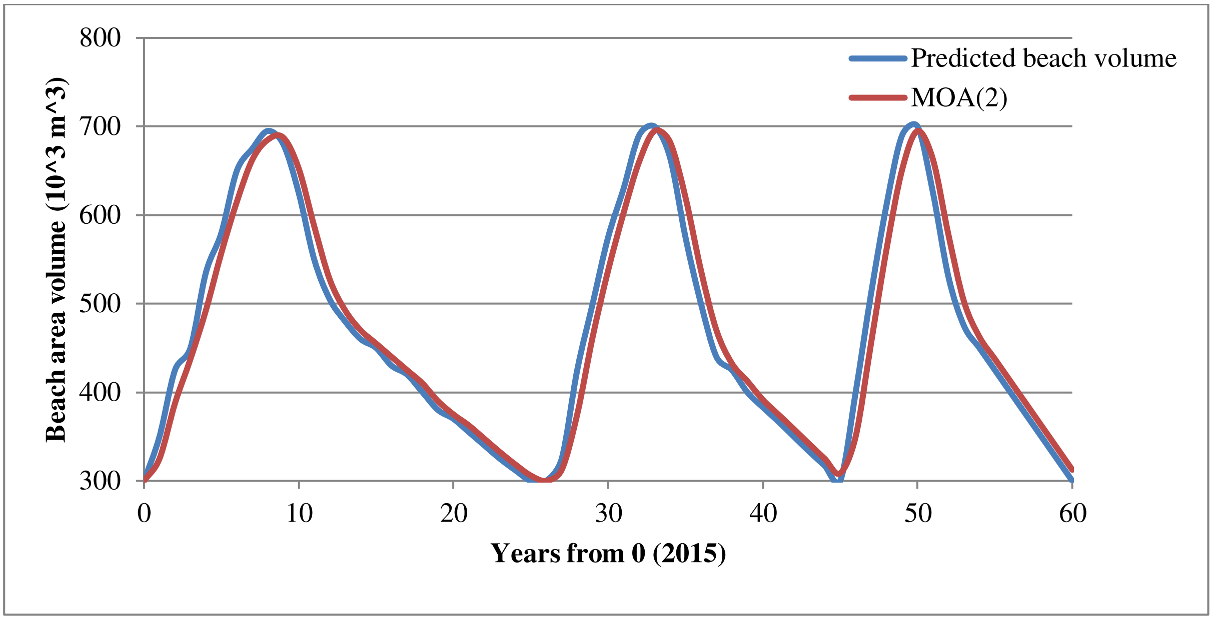


Figure 4.4.6. Projected Bed Nights with Climate Change, with and without Beach Nourishment (2015-2075).

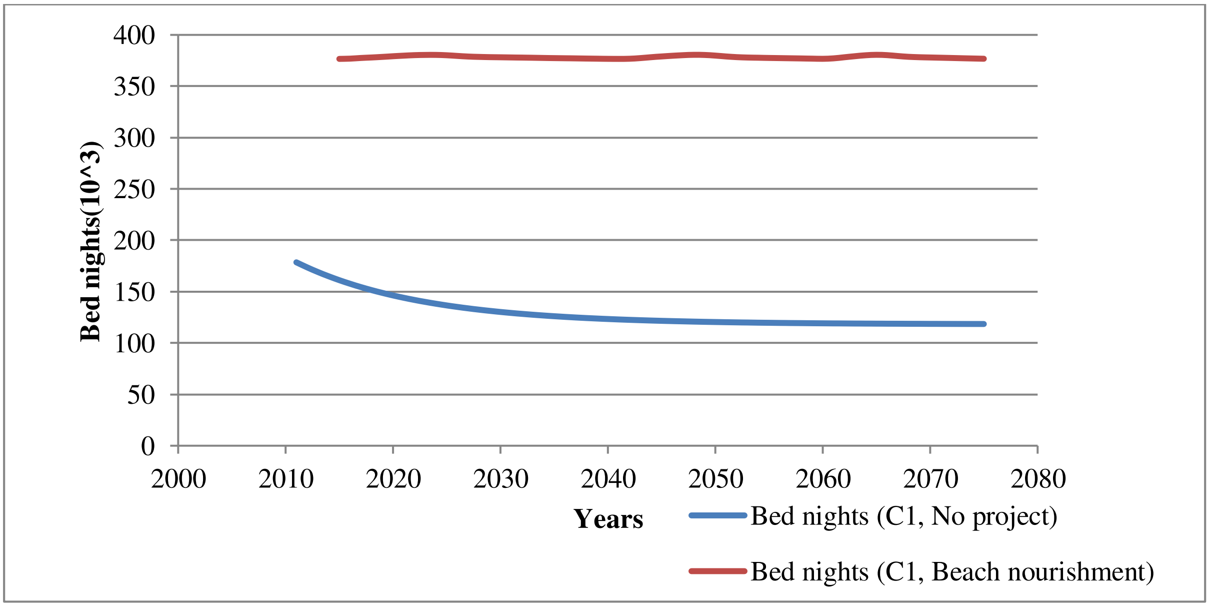
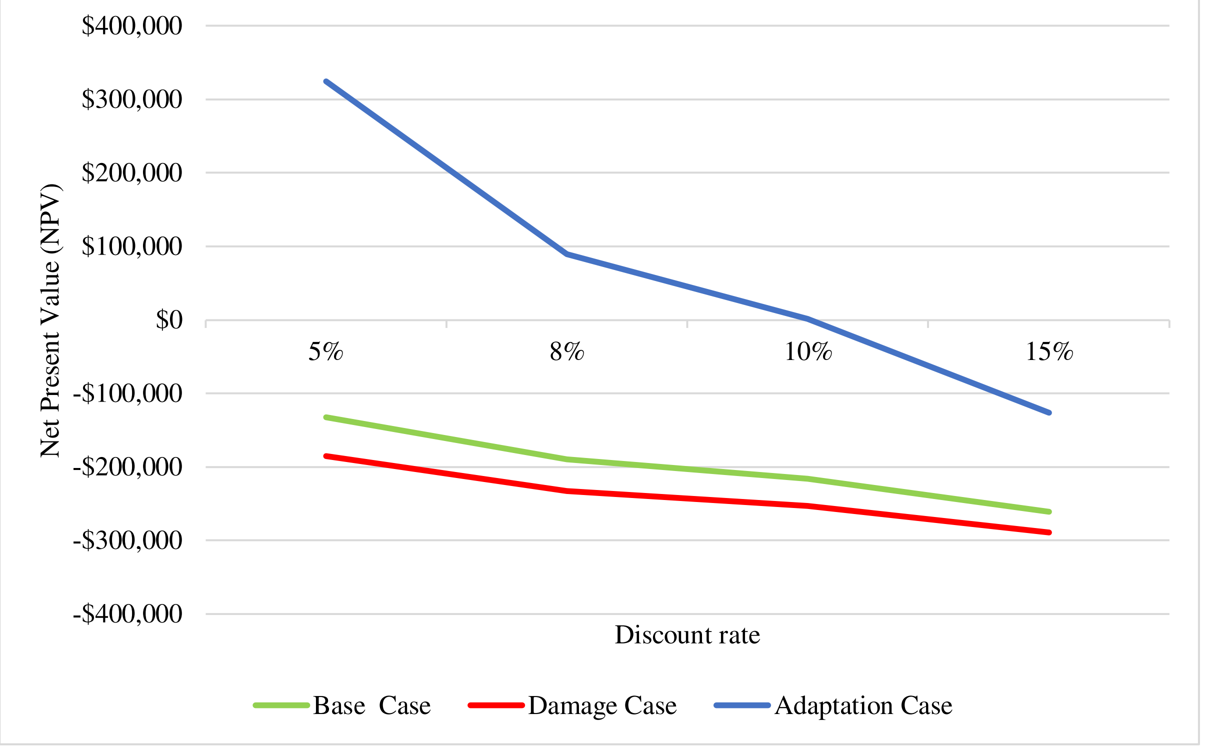


Figure 4.4.7 presents the graphic results for the net benefits of adaptation and for the economic feasibility of the beach nourishment program under a range of discount rates from 5 to 15 per cent. The red line in Figure 4.4.7 represents the net present value of long-term hotel profits with climate change, but without beach nourishment. The blue line in Figure 4.4.7 represents the net present value of long-term hotel profits

with climate change with beach nourishment. The blue line is also indicative of the net present value of the program in its own right, should it be undertaken, as a result of a conventional program BCA. Finally, the green line represents the positive difference between the other two, which is the appropriate measure for the net benefits of climate change.

This figure highlights two important results of the economic analysis. The net benefits of adaptation (green) are positive and large, measured in hundreds of million dollars, but decrease as the discount rate increases, as expected. However, the results of the conventional BCA (blue) could be disturbing to investors, as the net present value of the beach nourishment program, without comparing it to a reference case, becomes negative above a discount rate of 10 per cent. This discount rate (10 per cent) also happens to be very close to the internal rate of return (IRR) of the beach nourishment program.[50] Therefore, not only would the investors be concerned about the interest rate (and fixed loan costs) at which they borrow the capital to finance the program; they would also look carefully at their return on capital, reflected in the IRR, to see if it met their criteria.

Figure 4.4.7. Net Present Value Analysis of Beach Nourishment for the Base Case, Adaptation Case, and Damage Case, for discount rate of 5%, 8%, 10%, and 15%.



The full results of the adaptation BCA are presented in tabular form in Table 4.4.3

50 The internal rate of return (IRR) is the computed discount rate at which the net present value of the project is zero.

Table 4.4.3. Main Economic Results: Climate Change Damages, Net Benefits of Adaptation and Residual Benefits and Net Present Value of a Conventional BCA.

Discount Rate	Base Case	Damage Case	Adaptation Case	Climate Change Damages	Net Benefits of Adaptation	Residual Benefits
5%	-$132,060	-$185,417	$324,287	-$53,357	$509,704	$456,347
8%	-$190,029	-$232,444	$89,721	-$42,415	$322,165	$279,750
10%	-$216,045	-$253,209	$1,058	-$37,164	$254,266	$217,102
15%	-$261,079	-$289,229	-$126,448	-$28,150	$162,782	$134,632

The present value of climate change damages, if the climate changes and the nourishment program is not undertaken, ranges from about $53 million to $28 million over the four discount rates. The net present value of the avoided climate change damages due to the nourishment program (net benefits of adaptation) ranges from about $510 million to $163 million, depending on the discount rate. Since the net benefits of adaptation are always higher than the absolute value of climate change damages, the nourishment program produces positive residual benefits at all interest rates. However, as the previous figure indicated, the net present value of the nourishment program drops sharply as the discount rate is increased; it is almost zero at 10 per cent, and about -$126 million at 15 per cent.

Conclusion and Discussion

This example involved using a hypothetical data set of observed beach area volume and bed nights for a group of beachfront hotels to conduct an adaptation BCA of a very costly, long-term beach nourishment program, intended to increase the profitability of the beachfront hotels. The analysis was based on assumptions about how climate change would affect beach erosion due to increases in storminess, on-shore currents, and sea-level rise. Simulations from a hypothetical beach nourishment model were used to generate beach profiles for different levels of beach nourishment. The example was chosen to illustrate how a short-cut economic analysis, performed with just a spreadsheet, could be used in conjunction with complex, geophysical models of beach erosion to estimate climate change damages, net benefits of adaptation and residual damages/benefits. The results showed, interestingly, that the net present value of climate change damages on the beach was relatively large, of the order of tens of millions of dollars, while the present value of the net benefits of adaptation were on the order of hundreds of millions of dollars. Thus, the beach nourishment program also produced residual benefits of the order of hundreds of millions of dollars. However, this is not the end of the story, as it was found that, above discount rates of 10 per cent, the present value of the long-term profits of the hotel were negative, which could influence the decision of investors, whose hoped-for return on investment was above an internal rate of return of more than 10 per cent.

While this study was based on hypothetical data, there are two important issues that should be discussed about the economics of beach nourishment. First, the connection between GCM and RCM and sea-level rise simulations using standard climate change scenarios and the geophysical phenomena that lead to accelerated beach erosion are not as reliable as that between long-term changes in the means of temperature and precipitation and, for example, crop growth. This is, in part, because of the highly localized and widely varying nature of beach erosion processes, which can only be addressed using locally parameterized geophysical models. This is also due to the fact that the uncertainty about the link between climate change and sea-level rise is quite uncertain. Analysis of this so-called “deep uncertainty” should be addressed in economic analyses of long-run adaptation actions. This is because nourishment programs that involve large investments on the basis of uncertain information about the future may turn out not to work as planned due to unpredicted climate changes. One way to avoid this is to stage individual beach nourishment cycles based on the observed results over time, or so-called adaptive planning. This could have been analysed in the context of this example by assuming different rates of beach erosion and, therefore, different outcomes for the geophysical simulations of the quantity and timing of beach nourishments over time. An example of such approach, using a combination of real options analysis and robust decision-making in a water supply dam investment case, is Jueland and Whittington (2014), based on the work of Lempert and his colleagues (Lempert, 2013; Lempert & Groves, 2010; Lempert et al., 2002). In the following chapter we discuss deep uncertainty in detail.

A second key economic issue is that most beach nourishment studies that include economic analysis only value damages in terms of property loss or, as in this example, the financial net benefits of more pristine-looking beaches to beach owners and operators. These accounts capture the supply-side of the picture; however, valuations of the benefits to beach users are often omitted. Recent examples include Hinkle et al. (2013 and 2014) and Jin et al. (2013). However, as Penn (2013) points out, these types of studies do not include the benefits of improved beach activities for which users do not pay over and above their financial use costs. This is known as “consumer surplus”, which is the amount of money a beach user is willing to pay to use a beach, compared to not using it, less the amount they pay for access. Including consumer surplus net benefits in financial analyses of private beach owners or operators and investors does not actually make sense, unless these benefits can be captured by actual money payments, for example, when there is an entry charge is based on willingness to pay. However, it does make sense if the beaches are in protected areas and in cases where investors may be seeking donor assistance or domestic government support for environmental objectives.

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Flood gates of a small dam

5. Decision-making under Uncertainty

Prakriti Naswa and John MacIntosh Callaway, Jr.

Introduction

Climate has been changing ever since the formation of the earth. Anthropogenic activities have accelerated this phenomenon, leading to the problem of climate change. How does one identify these changes in future? One way is the frequentist[51] approach assessing the probability of an uncertain event, where historical data are extrapolated and past trends determine its future probability. The changes in climate variables come with a confidence level based on the historical record. However, the reliability of projections made using this approach depend on the length of the observed record and the underlying variability in it. Also, this is a statistical process and does not reflect the accelerated pace of climate change, unless some auto-regressive[52] process is introduced. In climate science, the past is not always a very good indicator of the future. At best, probabilistic approaches are useful for risk assessment. Another method is the Bayesian probabilistic approach (Knight, 1921; Freund, 1973), where future changes in climate variables are a result of expert judgements and other forms or objective or subjective data/inputs.

When policy decisions have to be made for the future, decision-makers sometimes assume, wrongly, that climate scientists will have perfect understanding of future states of the climate. To predict these changes is a difficult task, especially as the projections are dependent not only on the observed phenomena and interactions, but also on the policy decisions and behavioural choices that are made today. The IPCC defines uncertainty as "A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour" (IPCC, 2014). IPCC also presents likelihood scales and other quantitative measures to represent uncertainty. Walker et al. (2003) characterize uncertainty on a scale starting from the end of determinism to indeterminism. This spectrum consists of "statistical uncertainty", which can be defined in terms of statistical measures; "scenario uncertainty", which arises due to different underlying assumptions leading to a range in the outcomes; "recognised ignorance", which is outcome of ignorance of the mechanisms and functional relationships being studied; and "total ignorance", which is the opposite of and other extreme from determinism. Many researchers later reclassified these as shallow, medium and deep uncertainties and recognized ignorance respectively (Kwakkel et al., 2010). In this spectrum, we primarily focus on "scenario uncertainty" or "deep uncertainty", situated between uncertainty that can be characterized statistically and uncertainty that is complete ignorance.

Kandlikar et al. (2005) define deep uncertainty as an outcome of multiple scientific and social factors that limit the accurate quantification of climate variables (Kandlikar et al., 2005). Deep uncertainty arises out of ambiguity, disagreement among analysts and decision-makers, and a lack of information regarding

51 The frequentist approach to probability measures probabilities as an outcome of multiple trials or the long-run frequencies with which events occur.

52 An auto-regressive process is one in which future values are based on a weighted sum of previous values, i.e. the past determines the future.

the models that describe interaction among the system's variables, probability distributions representing uncertainty and evaluation of the appropriateness of alternative outcomes (Lempert et al., 2006). Kwakkel et al. (2010) define deep uncertainty as uncertainty where decision-makers cannot agree or do not know which scenario is representative or the order of each of the enumerated scenarios.

Uncertainty can also be represented by qualitative statements or in quantitative terms like probabilities. Initially, the only information available to perform such characterizations of climate uncertainty came from the use of the four emissions scenarios, based on the IPCC Special Emissions Report (IPCC, 2000). More recently, the results of the Ensembles Project (van der Linden & Mitchell, 2007) and the introduction of the concept of "Representative Concertation Pathways" (RCPs) by Moss et al. (2008) has been turned into a series of on-going RCP scenarios (Vuuren et al., 2011 & Wayne 2013). These are four sets of pathways that lead to radiative forcing levels of 8.5, 6, 4.5, and 2.6 W/m2 by the end of the century (Vuuren et al., 2011). They cover the 1850–2100 period, and some extensions have been done for projections up to 2300.

The Special Report on Emission Scenarios (SRES) by the IPCC in 2000 presented 40 scenarios based on four families or four qualitative story lines. The IPCC defines scenarios as "A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships." As such, these scenarios do not have an associated probability density function or discrete probabilities, although one assumption often made is that all these scenarios are equally likely. Even so, the climate projections based on these scenarios are merely representations of the storyline in climate variables, which are not predictions or forecasts.

The RCP 8.5 is a high radiative forcing extreme scenario. Some of its assumptions have been derived from the A2r scenario of the SRES. The RCP 6 scenario is a second intermediate pathway. The emission levels could be to the tune of 850 CO_2 eq. at stabilization after 2100, and average global temperature will increase in the range of 3.2 – 5.4°C towards the end-of-century w.r.t. baseline of 1850-1900. The RCP 4.5 is a stabilization scenario where again, like RCP 6, technologies are used to reduce emissions. The emissions could be to the tune of 650 CO_2 eq. at stabilization after 2100. These emissions levels are roughly half of the emissions that could be in the RCP 8.5 scenario. The RCP 2.6 is a low radiative forcing scenario with temperature increase projected in the range of 1.0 – 2.3°C during 2081-2100 w.r.t. baseline of 1850-1900. In this scenario, emissions are reduced substantially over time with a peak to the tune of 490 CO_2 eq. before 2100 (Chaturvedi et al., 2012; Riahi et al., 2007; Riahi et al. 2011; Vuuren et al., 2011). This just gives an indication of the wide range of projections available and the flawed assumption of policy-makers that climate scientists have perfect information.

Uncertainty also arises due to the downscaling of general circulation models to finer levels of geographical resolution. Downscaling also involves many assumptions in which global data is used in the process of generating regional data (Murphy, 1999). The general circulation models have a coarse resolution, and the geographical span is too large to make any relevant conclusions for local adaptation. If the global temperature is increasing by 2 degrees centigrade, it will not the same in all locations, and regional or local impacts will be different. Downscaling procedures can be statistical or dynamic in nature (Deser et al., 2012). In statistical downscaling, high-resolution climate data is generated using statistical relationships derived from the historical record. Dynamic downscaling uses a combination of regional topography, empirical observations and deterministic processes and boundary conditions derived from climate models to downscale GCMs to finer resolutions (Maurer & Hidalgo, 2008). In both the cases, the uncertainty in climate projections increases as the sources of non-stochastic variation increase.

In reality, while the climate models are becoming better, there is still a huge variation in the estimates from these models, and there are no indications of this wide variation becoming conclusive. As the inputs are variable, the decision-maker has to resort to ways of making decisions given this uncertainty in estimates. In general, in dealing with uncertainty, policy-makers have two choices. The first is to reduce the uncertainty. Reducing uncertainty implies that policy-makers have clarity about future climate states so they can make the right policy decision today. In an ideal world, more information can resolve the uncertainty, though this information comes at a cost. This concept is used in decision-making in finance and is called the expected value of information. In the context of climate change, this uncertainty may not be resolved. To wait until the uncertainty is resolved, without adaptive updating will practically halt the decision-making until the future time arrives.

The second alternative is to manage uncertainty by incorporating its implications into the decision-making process. This chapter focuses on the second option and introduces the issues that surround policy-makers when making decisions under uncertainty. In the subsequent sections, the modern and traditional approaches for making decisions under uncertainty are elaborated. Finally, the chapter concludes with one example of how economic losses, regrets, and benefits can be used to make decisions involving robust choices.

Decision-making Under Uncertainty

Having an understanding about general trends in climate variables gives policy-makers the ability to make better choices about the general direction of mitigation and adaptation policies. As adaptation is location-specific, for most adaptation options policy-makers need to know the range of changes in future climate variables at local scales. Having different scenarios and climate projections based on these changes raises concerns about their utility in decision-making. It is not possible to take make an unconditionally optimal decision today based on uncertain future climate states. Kelsey & Quiggin (1992) classify decision-making methods depending upon on whether they use subjective probabilities, unique non-additive probabilities or no probabilities at all (which itself assumes a uniform distribution of outcomes). Making a distinction between decision-making under uncertainty and decision-making under risks are two different things (Knight, 1921). Tossing a coin and selecting an outcome is decision-making under risk. The decision-maker knows all the possible future states, i.e. a head and tail and their probabilities, which is 0.5 each. Making decisions under uncertainty is complicated because the future states or their probabilities are not known.

Hallegatte et al. (2007) shows that in A2 scenario of SRES (closer to RCP 8.5), the future climate of Paris in 2080 will be closer to Córdoba (southern Spain). The present climatic conditions in both cities are very different. Córdoba has a subtropical-Mediterranean climate, while Paris has a European oceanic climate, which is colder than Córdoba's. Policy decisions on adaptation options like infrastructure planning have to be taken under current conditions, keeping in mind the future state of climate and the transition between them. This becomes a serious limitation when there are many options to choose from. In the A2 scenario, the planning for Paris has to be conducted in order to cope with a warmer climate. However, if the planning process has to follow projections for the B2 scenario, which is in contrast to A2, the decisions will be very different, for example, if the number of days when the temperature will be above 35 degrees Celsius in Paris is just one day on average, every year. At the end of the century, if this rises to twenty days in the A2 scenario vis-à-vis two days in the B2 scenario, the task for policy-makers is very difficult because of this broad range. These are just two scenarios and finding a relevant scenario among the many scenarios from SRES adds to the complexity of the decision-making process.

This is particularly pertinent for infrastructure adaptation decisions because their life span is much longer, "wrong guesses" about future climate states can be very costly, and decisions based on such factors as demand growth, safety and the need to replace aging infrastructure may also be costly to delay. For technology and infrastructure adaptation options, there is often little flexibility in changing the decision in the future, when there will be more clarity about climate conditions. This is particularly true of infrastructure that was designed and built under assumptions of a steady-state climate and a reasonably reliable understanding of climate variability. The decisions thus made in view of climate projections can turn out to be quite different from expected. Moreover, there is also the troubling problem that, even when planning infrastructure projects using stochastic approaches, different distributions of climate variables that fit the historical record almost equally well can have very different implications for climate impacts and infrastructure design (Lettenmaier & Burgess, 1978).

All adaptation decisions that are based on mistakes about future climate states have opportunity costs. Thus, reducing uncertainty in climate projections has economic value. Scientifically, there are limits to reducing uncertainty in climate projections. Conceptualizing damages arising out of an uncertain future has many issues in framing the problem context. Statistically extreme climate is represented in the tails of the distributions. With the increase in the variability and means of climate variables, the mass around these tails is increasing. Weitzman (2009, 2010, and 2011) calls them "fat tails". In this connection, he proposes a "dismal theorem" which states that a society's willingness to pay to guard against the potential damage from climate change is infinitely large, provided the society has a constant relative risk aversion and an uninformed prior view of the risks of climate change. This conclusion has also been criticized by researchers, as an unbounded willingness to pay is an outcome of the assumptions of the theorem, not the data (Nordhaus, 2009 and 2011; McKitrick, 2012). However, short of these doomsday predictions, a more important problem is that the reliability of climate projections based on values that lie on the tails of distributions is much lower than for values closer to the means of the distributions of climate variables. This is one of the more important reasons for building greater flexibility into structures exposed to extreme events.

Traditional Approaches for Dealing with Uncertainty

The Expected Value Approach

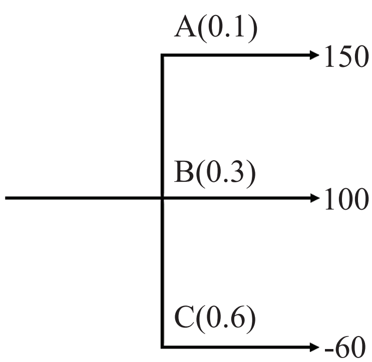
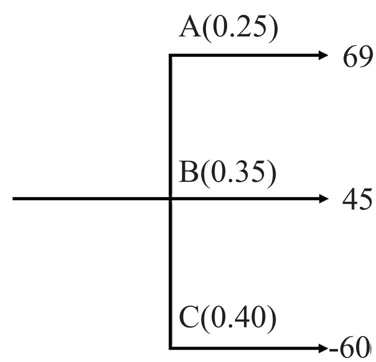
Probabilistic approaches are often used to assess risks while making decisions. The expected value approach is one of the traditional ways of dealing with uncertainty. The expected value of an investment is equal to the net present value of the capital cost plus the sum product of the net benefits from all possible outcomes and their respective probabilities. The following equation (equation 5.1) gives the expected value (EV) where P_i are the probabilities and X_i are the values of utility, costs, benefits, or net benefits, as the case may be.

$$EV = \sum_{i=1}^{n} Pi * Xi$$

Equation 5.1

To begin with, let us assume a two-scenario case with each scenario having an equal probability, i.e. 0.5 of one accruing net benefits of 100 units and the other bringing about a loss of 100 units. In this case, the expected value is 0. The decision-making process will also depend on the decision-maker. A risk-averse person would not necessarily take the risk because of his/her aversion to economic gains that come with unacceptable risks. A risk-taker acts in the opposite way: as economic gains increase, they are willing to accept more risk. A risk-neutral person is indifferent between the two options. In this example, since the probabilities are the same and the payoffs are opposite, the situation of a low-probability high payoff or high-probability low payoff does not arise. These can be understood with two parallel examples. Suppose there are three scenarios A, B, C, with probabilities 0.1, 0.3, and 0.6 with net payoffs for each scenario being 150, 100, and -60 units respectively (Table 5.1). The expected value in this case is 9. Here, although the expected value is positive, a risk-averse person may not take the risk because the probability of a loss is greater than 50 per cent. A risk-averse person fears loss more than the potential gain. A risk-neutral person may still accept this because his decision is based on the expected value, which makes him/her neutral to the options until the time the expected returns are positive.

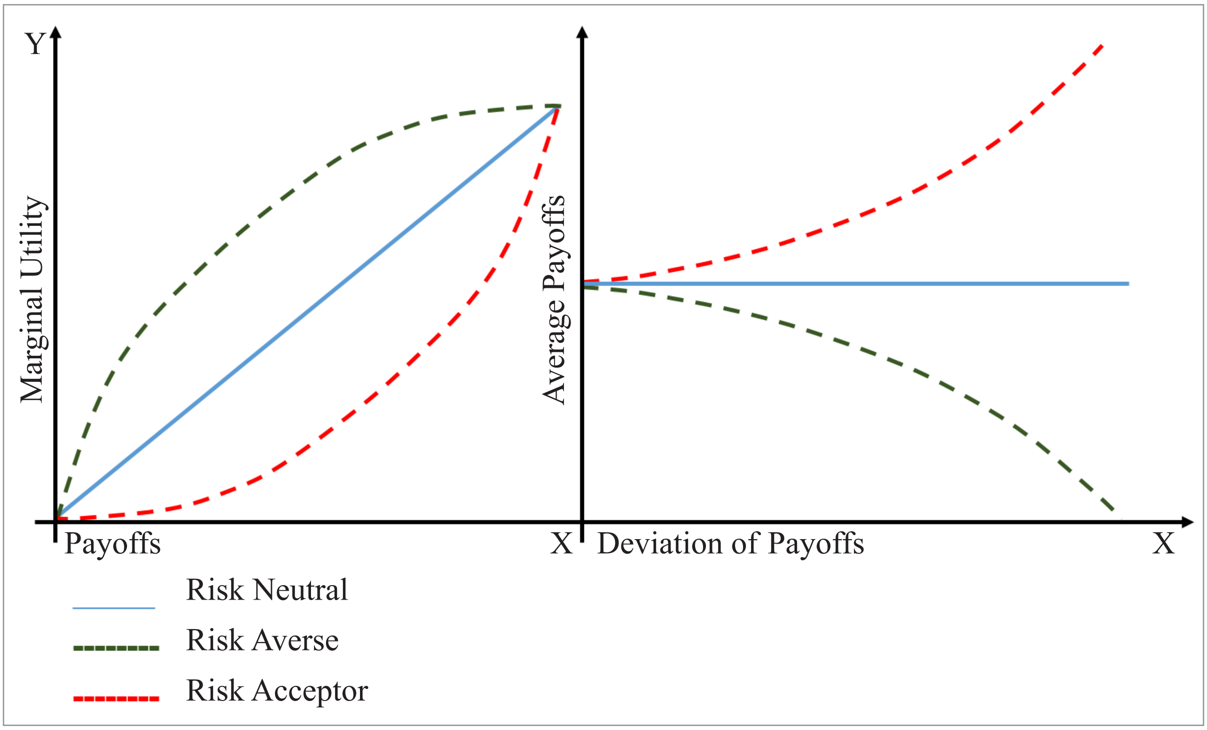
Table 5.1. Examples of Expected Value.

Example 1	Example 2
= 150 * 0.1 + 100 * 0.3 + (-60) * 0.6 = 15+30-36 = 9  	= 69 * 0.25 + 45 * 0.35 + (-60) * 0.40 = 17.25+15.75-24 = 9 

If the probabilities for the three scenarios were 0.25, 0.35 and 0.40 with respective payoffs as 69, 45, and -60 units, the decision-makers may choose differently, although the expected value in this case as well is 9. The risk-averse decision-maker may not be so averse to this situation as compared to the previous one. The first case reflects the low-probability high-return case, where, at the extremes, the payoffs are higher. The second case is more balanced.

Figure 5.1 shows the risk-neutral, risk-acceptance and risk-averse behaviour of decision-makers. On the left side, the X-axis shows the payoffs, and the Y-axis the marginal utility for the decision-maker. The marginal utility increases with payoffs for the risk-taker. On the right side are indifference curves, the X-axis shows the deviation of pay-offs, and the Y-axis the average payoffs. A risk-acceptor would prefer high payoffs, irrespective of the deviations, while the risk-averse person will not prefer options with higher deviation in pay-offs.

Figure 5.1. Risk-neutral, Risk-acceptance and Risk-averse Behaviour of Decision-makers.

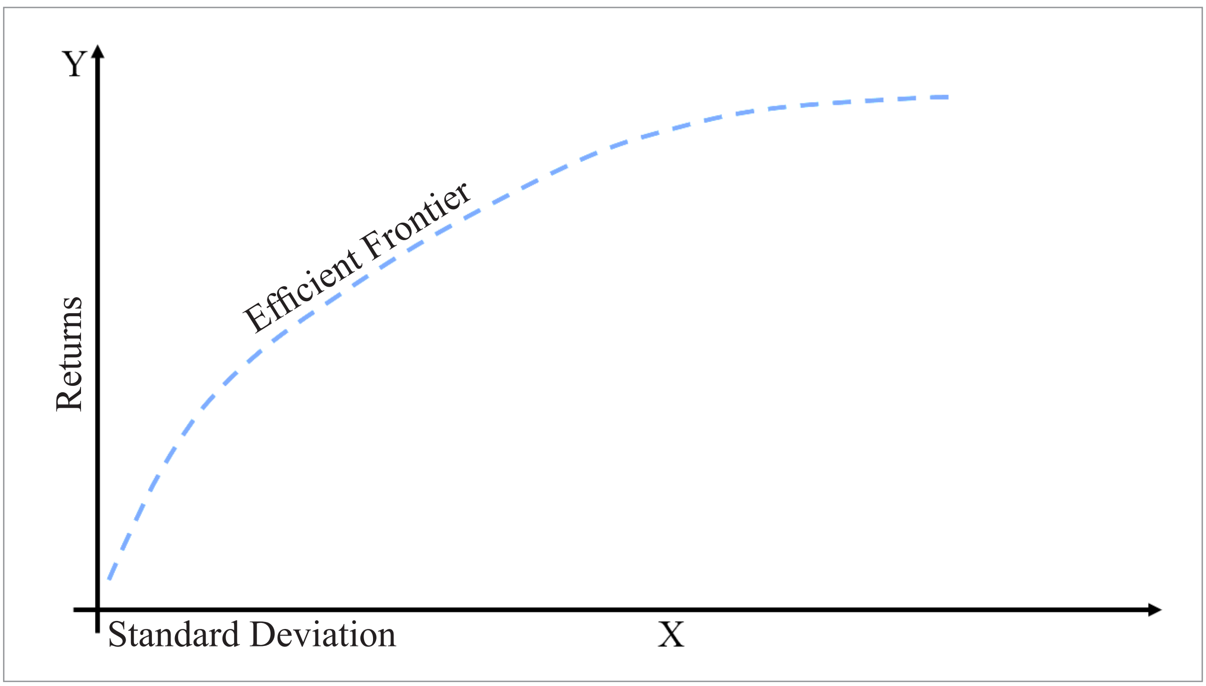


One problem in applying the expected value approach to climate change projections is that of establishing probabilities. These issues with probability arise in any risk assessment based on climate projects. *Firstly*, the past is not a good indicator of the future when it comes to climate change, unless one has a long time series that takes climate change into account. This is because anthropogenic activities are increasing the frequency and intensity of climate-induced events. The rate of global temperature increase in the last fifty years (0.13°C ± 0.03°C per decade) is twice as much as for the last hundred years (IPCC, 2007). Therefore, extrapolation based on historical data loses its relevance. *Secondly*, since future scenarios do not have probabilities, in principle there is no scenario that is any more or less likely than any other one. Even if some ordinal arrangement is found among the scenarios where a decision-maker is aware which scenarios are more likely and which ones are less likely, it is still quite difficult to establish logical probabilities for each scenario. The subjective nature of probabilities adds vagueness to the assessment. *Thirdly*, economic assessments of climate change impacts and adaptation are influenced by many sources of risk and uncertainty that interact with climate change, such as economic development, whose partial influence on climate change damages and the net benefits of adaptation is rarely isolated from the partial effect of climate change. In practice, there will be many more scenarios and different payoffs for different actions, making this simplistic approach irrelevant. *Fourthly*, in general, using the expected value approach averages payoffs. However, adaptation in the face of very extreme climatic events is a fundamentally important issue, whose welfare implications are often missed when multiplying a minuscule probability by a very large economic value. In addition, using expected values in cases of extreme events often does not take into account other risk-related factors that are economically important, such as the time it takes to recover from extreme events. *Fifthly*, the method does not take into account robustness, i.e. the potential of a decision or policy to deliver acceptable results over a wide range of climate outcomes. *Finally*, if the decision-maker is risk-averse or a risk-acceptor, in both cases the choice is being guided by the decision-maker, who may not reflect society's preferences (Schneider & Kuntz-Duriseti, 2002). The assumption that the decision-maker is risk-neutral is big and it is not reflective of reality.

Fuss and McFadden (1978) explained this in the context of ex-ante plant design. Consider a situation in which a firm has to choose between a technology that is optimal in one future state and another technology that does reasonably well irrespective of the future state. The firm may choose the second option, although it is not optimal. The first option does well only in one future state, and if that does not happen, the technology decision fails. In the second case, though the maximum returns are less, the bottom line has a limit (Fuss & McFadden, 1978). This is analogous to making adaptation policy decisions for the future. Options may be optimal with respect to a specific future state of climate, but for some types of capital investments (power plants in the authors' case), they argue that flexible plant designs that can operate over a wide range of weather-driven peak power demand periods need to sacrifice economic efficiency for flexibility. In a slightly earlier paper, Matalas and Fiering (1977) echoed the same sentiments with regard to the design of water resources supply infrastructure, emphasizing the importance of building operational (short-run) flexibility into the design of reservoirs to create robust, long-run investments.

Trade-offs between risks and returns have to be considered, i.e. the expected benefits have to be put in context with the standard deviation of payoffs. While variation in returns is not desirable, it cannot be avoided. In plotting risks and returns on a graph (Figure 5.2), the objective is to achieve the highest returns with the lowest risks.

Figure 5.2. Efficient Frontier in Portfolio Theory.



In the context of portfolio theory, this has been described as the efficient frontier (Markowitz, 1952). Markowitz (1952) defined the efficient frontier as the various combinations of securities that yield maximum returns for a defined level of risks. Anything above it is not possible, and anything below is sub-optimal. The efficient frontier, as seen in Figure 5.2, is a curved line, which is due to diversification. This may also hold true for mixed strategies in adaptation. However, there are many other complex considerations in the case of adaptation interventions vis-à-vis a portfolio of securities.

Decision Theory (Maxi Min, Maxi Max, and Mini-Max approaches) and Expected Value of Information

Decision-making for adaptation policies and projects often cannot wait until perfect information is available, particularly if their primary purpose lies in the area of economic development. Hence, decisions have to be taken in an uncertain environment. The various tools and approaches used in decision-making need not necessarily clear the uncertainty factor or help a decision-maker come up with unambiguous decisions. Decision-making processes can also be facilitated through non-probabilistic ways and through mathematical ways. In the following sub-sections, we describe various non-parametric methods of decision-making under deep uncertainty that do not use probabilities. The decision-making process through these non-probabilistic decision criteria, i.e., maximin, maximax and mini max, have been explained through an example of making decisions under uncertainty. None of these strategies takes into account the probabilities, range or standard deviations while choosing the appropriate action.

To understand these decision criteria, let us suppose there are three adaptation options to choose from, namely Option 1, Option 2, and Option 3, and they are well suited to a business-as-usual scenario, a climate change scenario and sustainable adaptation (development) scenario respectively. A business-as-usual scenario is one in which climate change takes place in accordance with an expected trend, and planned policies continue into the future. This could be a high emissions and high climate change scenario. The climate change scenario is one in which some actions are taken by the authorities and other stakeholders, but the efforts are not enough to arrest the change, i.e. mitigation is below BAU and the climate changes more than BAU. The sustainable development scenario is the aggressive scenario, which implements all climate-friendly policies for aggressive mitigation, and climate change is arrested. Each of the adaptation options is more suited to one particular climate scenario, for which it yields maximum net benefits: if for that particular scenario a different policy is chosen, the net benefits are sub-optimal. Table 5.2 gives the payoffs or net benefits from each of the strategies under the future climate states. This table will be used to assess the decision criteria.

Table 5.2. Pay off Matrix (Net-Benefits of adaptation strategies for each scenario).

Actions	States		
	BAU	*Climate Change Scenario*	*Sustainable Development Scenario*
Option 1	100	100	100
Option 2	50	200	200
Option 3	10	125	300

Maximin

One of non-probabilistic decision criteria is the '**maximin**' option. This implies choosing the best from the worst outcome. In this criterion, the decision-maker choses the option that yields the maximum value of the minimum payoffs. This criterion also implies a pessimistic or risk-averse nature, where the decision-maker would want to pick a choice with the least downside. A common definition of the maximin decision criterion is as follows:

> "In decision theory, the pessimistic (conservative) decision making rule under conditions of uncertainty. It states that the decision maker should select the course of action whose worst (maximum) loss is better than the least (minimum) loss of all other courses of action possible in given circumstances. Also called maximin regret or minimax criterion." (Business Dictionary, n.d.)

Table 5.3 shows the net benefits for each adaptation option and the choices under the maximin criterion. For each climate scenario, there is just one most suitable climate adaption action, which is also reflected in the higher value of net benefits in the specific scenario. Since no other strategies are so suitable, they operate at sub-optimal levels.

Table 5.3. Maximin Decision Criteria (Net benefits in million USD).

Actions	States			
	BAU	*Climate Change Scenario*	*Sustainable Development Scenario*	*Maximin*
Option 1	100	100	100	**100**
Option 2	50	200	200	**50**
Option 3	10	125	300	**10**

Option 1 is most suitable for BAU, and in this case the minimum payoffs are 100 million USD. Similarly, the minimum payoffs with Options 2 and 3 are 50 million and 10 mission USD respectively. Now that the minimums are known, the decision-maker is aware of the worst possible outcome in each case and therefore picks the best out of these numbers. From the decision-maker's perspective, this is the safest approach and he is assured of some minimum returns. Option 3, which has the payoff for 100 million USD, is chosen.

This decision criterion involves choosing the best from the worst and ensures that nothing worse than this can happen. This criterion is for risk-averse decision-makers who prefer to focus on the worst possibilities and follow a protection strategy.

Maximax

In **maximax** criteria, the decision-making process is based on choosing the strategy with maximum returns. This implies choosing the best from the best outcome. This criterion represents optimistic or risk-taking decision-makers who assume that the downside will not occur, or who are willing to tolerate the risk. The following matrix shows the maximax criteria. A common definition of the maximax decision criterion is as follows:

> "In decision theory, the optimistic (aggressive) decision-making rule under conditions of uncertainty. It states that the decision-maker should select the course of action whose best (maximum) gain is better than the best gain of all other courses of action possible in given circumstances." (Business Dictionary, n.d.)

Table 5.4. Maximax Decision Criteria (Net benefits in million USD).

Actions	States			
	BAU	*Climate Change Scenario*	*Sustainable Development Scenario*	*Maximax*
Option 1	100	100	100	**100**
Option 2	50	200	200	**200**
Option 3	10	125	300	**300**

As can be seen from the payoff matrix, each action has different payoffs in different scenarios. Among these, maximum pays-off for every option are chosen. Finally, the strategy that yields the maximum among these is selected. In this case it is Option 3, which has a payoff of 300 million USD. This strategy does not consider the downside of the actions. Therefore, if there were any possible negative pay offs in the matrix, they would be ignored while choosing the highest pay offs. This strategy is for risk-takers.

Minimax

The minimax criteria are based on regrets and aim to minimize the possible loss for a worst case. The matrix for minimax criteria should represent the losses. This criterion represents the opportunistic decision-maker. The matrix likewise represents the potential losses when an option is unsuitable for the future state is chosen. The following matrix therefore shows the opportunistic loss or regrets if a wrong choice is made, i.e. if the decision-maker had chosen one option over another option, how much better could he/she have done relative to the choice that was not made? A common definition of minimax decision criterion is as follows:

"A principle for decision-making by which, when presented with two various and conflicting strategies, one should, by the use of logic, determine and use the strategy that will minimize the maximum losses that could occur. This financial and business strategy strives to attain results that will cause the least amount of regret, should the strategy fail." (Business Dictionary, n.d.)

Table 5.5. Regret Table for Minimax Criteria (in million USD).

Actions	**States**			
	BAU	***Climate Change Scenario***	***Sustainable Development Scenario***	***Minimax***
Option 1	0	0	0	**0**
Option 2	-150	0	0	**-150**
Option 3	-290	-175	0	**-290**

In the case of minimax decision criterion, one considers the losses incurred by choosing a sub-optimal option. From these losses, the minimum is chosen. In the example above, if Option 1 is chosen, the payoffs are equal in all the scenarios, and hence there was no suboptimal decision. In case of option 2, if a BAU scenario occurred, a potential of 150 million USD of benefits is not realized. In option 3, if a BAU or climate change scenario occurs the opportunity costs (a loss) are 290 million USD and 175 million USD respectively. Finally, for choosing the option that minimizes the maximum loss, Option 1 is chosen. The maximin decision criterion assumes the worst and is based on the opportunities missed by making the wrong choices. This rule is less pessimistic than the maximin decision criterion (Ranger et al., 2010).

In all the above criteria, the probabilities of occurrence are not taken into account, and only a scenario analysis is carried out. Hence, for any changes in the assumptions of climate models, the decision criteria remain robust, but since the payoffs or regrets could change, the choice of the options may also change. There are no advantages or disadvantages to any of these criteria. It is usually the decision-maker's risk perception that guides the choice of these criteria.

However, there is a possibility to improve the decision-making process by acquiring more information. Sometimes information is accessible by payments, which also brings up another question for the decision-maker on how much should the s/he be willing to pay in order to obtain better payoffs in the decisions. This brings us to the related concept of the expected value of perfect information elaborated in the following section.

Expected Value of Information (EVI)

The concept of expected value of information (EVI) is traditionally found in capital budgeting and represents the price that one would be willing to pay for perfect information. The applications are similar in the domain of policy decisions for climate change. Policy decisions can be improved when information regarding the problem context is available. Usually complete information is never available. However, there is value in better information that can improve the reliability of our estimates and/or is worth waiting for. This is also useful in sequential decision-making. In the context of policy decisions on climate change, this information can (among other things) be applied to the nature of future climate states. Whenever new and relevant information is made available to a decision-maker, he/she can make a more informed decision. For example, a policy-maker wants to carry out afforestation in small village. His decision regarding the choice of tree species will change if he is provided with technical reports on the kinds of plants that are suited to the region. His decision-making potential is likely to improve further if he knows the preferences of those individuals who would be more willing to accept the policy change in accordance with their preferences.

EVI is defined by how much a decision-maker is willing to pay for perfect information (or as the upper limit for what a decision-maker would be willing to pay for additional "imperfect" information!) (Bruce et al., 1996). The information comes at a cost, and the decision-maker has to assess the trade-offs for this additional information (Hammitt & Shlyakhter, 1999). The expected value of perfect information is the difference between the expected value of the decision made with perfect information and of the decision made with current information. Mathematically this means that EVPI is the difference between "Expected Value Under Perfect Information (EVUPI)" (calculated as the sum product of the maximum payoff in each of the future states and the probability of the future states) and "Expected Value" of the best action with imperfect information. Let us use an example similar to the one described above to calculate the EVPI.

Suppose we have three potential adaptation options and three possible future scenarios whose probabilities are known. In this case, the expected returns for each adaptation option will be the sum product of the payoffs in different scenarios with the probability of occurrence. For all these future states there is also a maximum possible return, which is the sum product of maximum payoffs, with the probabilities, and is called the expected value with perfect information. The difference of this value with the maximum expected payoff gives the expected value of perfect information (EVPI). This is demonstrated in Table 5.6.

Table 5.6. Calculating EVPI (Pay offs in million USD).

Actions	**States**			
	BAU	**Climate Change Scenario**	**Sustainable Development Scenario**	***Expected Return***
Option 1	100	100	100	100
Option 2	25	200	200	165
Option 3	10	125	300	154.5
Probability	0.2	0.5	0.3	
Max Payoff	100	200	300	
Expected Value with Perfect Information (EVwPI) i.e. ∑Max Payoff * Probability				**210**
Highest Expected Value (EV Max) i.e. max of expected returns				**165**
Expected Value of Perfect Information (EVPI), i.e. EVwPI – EV Max				**45**

In practice, for decisions under deep uncertainty, the concept has limited utility. For good reason, expected values are calculated based on probabilities of future states, which is probably not ideal for various reasons discussed in this chapter. Information related to the future state of the climate can improve decision-making but, given the uncertainties involved, it may take a long time before the future state can be known. Often, some of the information can only be available with the passage of time, which may or may not be true in the case of relevant climate change information. The value of EVPI is also limited in the sense that it can only be useful when it comes in sufficient time to allow for corrective action (Yohe, 1996). The point here is that the cost of waiting for perfect information may be greater than the net benefits of not waiting and making do with less than perfect information, an interesting topic for future research on deep uncertainty.

In general, the primary problem with non-probabilistic approaches is also the need for *a priori* knowledge of all possible future states and their payoffs. Another problem, mentioned by Hammitt (1995), is that such an approach ignores the costs and benefits of surprises and mistakes. To put it simply, determining the prior distributions does not account appropriately for the extreme consequences that lie on the tails of the unknown probability distributions. As the frequency and variability of climate variables is increasing, these prior probabilities may be underestimating the downward impact. In addition, this approach leaves little room for the kind of flexibility that can be built into infrastructure that Fuss and McFadden (1978) and Matlas and Fiering (1977) have suggested. Finally, making decisions on climate polices goes beyond the payoffs, as the criteria should also take into account the preferences of stakeholders. The final choice of decision through these methods may not necessarily be strongly rooted in economic, technological and social factors.

Real Options Analysis

The above example of a decision tree (in the section on expected values) represented an overtly simplistic view of reality with clear options, probabilities etc. The payoffs are simply being discounted without assessing the actual possibilities associated with the option. In reality, the decision analysis may not stop at the first level. Real options are the non-financial options that represent the rights while executing adaptation decisions such as those of flexibility, expansion and deferral (Brealey, Myers, & Allen, 2011; Dixit & Pindyck, 1994). Valuation of these options many times changes the appropriateness of the decision for the problem; a potentially bad investment in an adaptation option may often become good investment when the real options are taken into account (Anda et al., 2009; Damodaran, 2008). Decisions that pertain to high capital value and that are long term in nature may benefit from real option valuation. In the context of climate policy decisions, the following are some of the examples of real options:

- The option to abandon a capital investment. To reduce dependence on conventional sources of energy, policy-makers decide to invest in a hydropower project. While implementing the project, it is realized that it is not suitable because of the limited availability of water. The option of abandoning the project, rather than maintaining it as a “white elephant” is a real option.
- The option to expand. Taking forward the above example, it may be impossible or very expensive to increase the generating capacity of a hydropower plant. The designs of such plants are based on many factors, such as the geography of the location, the relocation of villages that will be submerged etc. Therefore, increasing the height of the dam to increase its generating capacity after it is in operation may not be a real option. On the other hand, if a solar or wind farm or some other renewable resource-based generating technology is proposed as an alternative, the possibilities for expansion do represent real options. Suppose the current set-up in the solar farm generates 200 MW of power and is connected to the grid; then expansion by another 50 MW is possible by adding more solar panels to the farm.

- The option for incremental investment. Suppose grid mechanisms for a solar farm need upgrading with next generation of smart grids. For a solar farm, there is a possibility for upgrading. In a decentralized system for generating power it may not be possible to upgrade technologies, and in many cases a total replacement may be required.
- The option to defer investment. In a solar farm, there is the potential for a phased expansion. If the mechanics of financing are such that they depend on the performance of existing work done and could be made available only in phases, then the solar farm can still produce electricity (not to full efficiency) and provide power for its users. In a hydropower project, there is no such possibility: electricity generation happens only when the entire project is complete.
- The learning option. In policy options, concerning people there is a learning curve, which could make the option perform more efficiently than its peers. In the context of climate change adaptation, these options could involve the capacity-building of vulnerable communities.

To put the policy-maker's dilemma simply, what would be his or her choice if one adaptation action entails commitment to a specific technology for a fixed period of time with no possibility of a technology switch, vis-à-vis a technology which would allow for a switch when a new technology becomes available? Suppose that the policy-maker has to choose between promoting rainwater harvesting and other conservation measures (Alternative A) and building a check dam (Alternative B) to meet the water demand in a village (Table 5.7). Let us assume that in this specific context there is no scope for expansion and learning in the check dam, while for rainwater harvesting coupled with conservation measures there is the option to expand and the scope for learning. If the discounted net benefits of the two options are calculated, alternative A has negative payoffs at the end of 't'. This is because the training for water conservation may not yield immediate results, and rainwater harvesting may not meet the demand adequately. On the other hand, a check dam could fulfil the unmet needs immediately.

If the potential for expansion and the learning curve of the users is included in alternative A, there is a possibility of further benefits of 165 or 385, which, when discounted at 10%, puts the two alternatives A and B at par with each other. In the first case, the choice was clear, as 'A' has a negative payoff and 'B' has a positive payoff. After including the payoffs from the real options, the choices are no longer so clear. The issues with real options also are similar to traditional decision analysis forms, which include the choice of discount rate (Tol, 2003), establishing future states and their probabilities, estimates of benefits, possibilities of extremes etc.

Robust Decision-making

There are many traditional approaches to dealing with uncertainty. However, we close this topic section with a last subsection on robust decision-making. Making decisions under risks with known or subjective probabilities is less complicated compared to making decisions under uncertainty. Frank Knight (1921) explains this difference simplistically. When a decision-maker is making a decision under risk, he may not be able to predict future states or outcomes; however, because the possible future states are known, there is the possibility to assign prior probabilities and using Bayesian approaches in making the decision (Knight, 1921). As stated throughout this chapter, this becomes difficult in the case of uncertainty: the future states of climate are not known with the degree of reliability needed (ideally) to guide local adaptation actions; and the emissions scenarios that drive global climate models at both the global and regional levels have no stochastic basis.

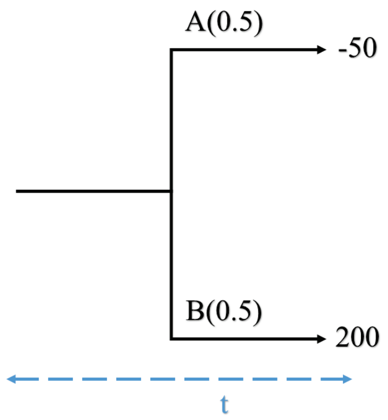
Table 5.7. Example of Real Option.

<table>
<tr><td>Discounted payoff at the end of t (Without Real Option)

A: -50

B: 200</td><td>Discounted payoff at the end of t (With Real Option of expansion and learning)

A: -50 + [0.5*(165)+0.5*(385)]/1.1 = -50 + 250

B: 200</td></tr>
<tr><td>
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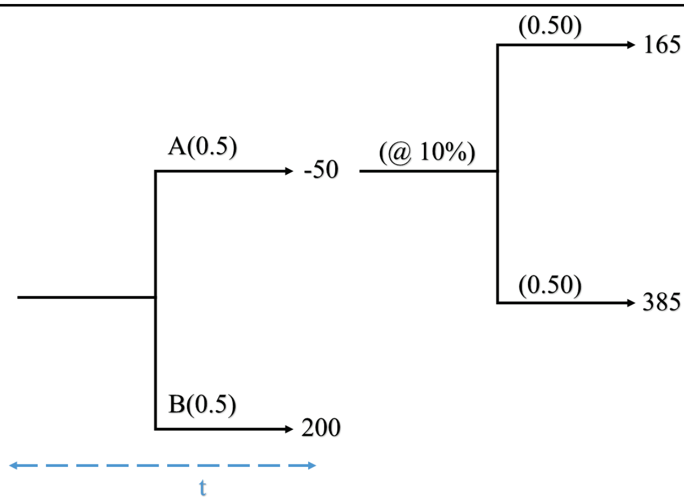
<tr><td></td><td>
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</table>

Thus, many traditional approaches to decision-making often fail under these conditions of deep uncertainty because they are sensitive to assumptions made regarding the future state of the climate. As the assumptions change, so does this future state, which often makes the choice of adaptation strategy redundant or somewhat irrelevant. Uncertainty can be reduced by improving the climate forecasts or improving probabilities, but it cannot be eliminated entirely, and hence decisions have to be made under uncertain future climate conditions. By delaying some forms of adaptation until there is better information about future climates, we could be foreclosing either on options to adjust to existing climate variability that may work well under future climate states, or on long-run investments that may be climate-sensitive, but have objectives other than avoiding climate change damages (which they may well do anyway).

One possible but not necessarily satisfactory outcome of the varying degrees of uncertainty is the precautionary approach. It is generally understood that to achieve sustainable development, policies must be designed based on the precautionary principle. This principle states that "if an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Raffensperger & Tickner, 1999). This is basically a safety-first approach using a risk-avoidance criterion that comes close to minimizing the maximum damage. Decision-makers take a very cautious approach while making decisions for interventions in adaptation. The drawback of an overtly cautious approach is that it may exhaust a lot of resources (high opportunity cost) even though the system may not need so many precautions.

Many of the conditions that determine the uncertainty in climate projections are not known and cannot be accounted for. Reducing uncertainty by waiting for better, let alone perfect information to adapt to climate change has its limitations when it comes to infrastructure investments that will last well into the future and are hard to "reverse" once they are built due to their "lumpiness". The problems with conventional approaches to dealing with risk and uncertainty have already been well enumerated. The question is how to replace these approaches with methods that would not end up making future choices random. This is where Robust Decision Making (RDM) comes into the picture.

RDM is a concept developed by the RAND Corporation in the United States. RDM isn't really a method; it is an analytical framework that facilitates decision-making processes by helping decision-makers identify potential adaptation strategies, identify their vulnerability to a wide range of climate projections (hereafter referred to simply as "ensembles") and evaluate trade-offs between them, using this information to point to the most robust strategies that perform well over a wide range of future climate scenarios, thereby managing the shocks/surprises in a better way. The process of identifying robust strategies ranges from using robust optimization techniques to quantitative scenarios and other heuristics (Lempert & Collins, 2007; Rand Corporation, 2013). Robustness should not be confused with resilience. RDM does not focus on optimality but on achieving intended resilience objectives (Jeuland & Whittington, 2014). The operational flexibility to cope with many different future states while achieving one's intended objectives leads to robustness. Resilience is a property of a system viewed externally, i.e. in response to climate change, while robustness is an outcome of the choices made by actors within a system. RDM uses different definitions of robustness, two prominent ones being:

- Trading optimal performance for less sensitivity to weak assumptions; and
- Performing relatively better on a wider range of plausible futures than one specific scenario (Hall et al., 2012; Lempert & Collins, 2007; Rand Corporation, 2013).

The RDM process is technically the reverse of the traditional decision-making approaches. There are three broad steps in the process. It begins with experts generating and interpreting information relevant to the decision and then, on this basis, determining the strategies and objectives. At the end of this step, goals, uncertainties and the strategy under consideration are identified. Next, analysts use computer models of several assumptions or climate scenarios to determine how the strategy under consideration performs in a range of plausible future scenarios. Finally, clusters of scenarios are identified which highlight the specific policy's vulnerabilities. This process is continued until a robust strategy is identified.

Part of RDM is not a new idea, for the approach and its underlying principles have been used in various domains other than climate change-related decision-making under uncertainty. Earlier publications by Fuss & McFadden (1978) have emphasized the need for flexibility over economic efficiency in planning weather-sensitive infrastructure, while Matalas & Fiering (1977) argued that operational flexibility should be built into reservoir designs so that they could perform well over a wide range of run-off events and patterns.

However, neither team of authors was doing this in the framework of deep uncertainty, and instead both were addressing weather and existing climate variability with known but perhaps “fuzzy” probabilities).

According to Lempert & Kalra (2011), RDM has three important characteristics. *First*, it reverses the order of traditional decision-making approaches of, first, predicting future states of nature and then basing actions or polices based on the adverse impacts of these changes. Instead, RDM begins with one or more strategies and then analyses their ability to meet the adaptation objectives over a broad range of existing climate projections, employing various non-parametric decision criteria to decide which strategies perform best over these “ensembles” of climate projections. RDM identifies the steps involved in reducing the vulnerabilities and then analyses the trade-offs. In traditional approaches, the characterization of uncertainty determines the status of vulnerability and subsequently the vulnerability reduction strategies. *Second*, RDM characterizes uncertainty with more than one view of the future and considers a wider range of scenarios than traditional approaches. The latter assign probabilities, and decisions are based on scenario(s) that are more likely than the others. *Finally*, RDM seeks robust decisions that perform under a wider range of future scenarios than optimal decisions that do very well in one best-estimate scenario. RDM does not attach restrictive conditions to decision-making, unlike precautionary approaches, but emphasizes alternatives that perform well in a range of plausible future states.

To put this in the form of an example, let us take a village whose economy primarily thrives on agriculture but is facing the problem of an uncertain water supply. Extreme changes in climate are making drought conditions common in the village. The villagers now feel the need to adopt an appropriate adaptation strategy to deal with the changing climate. They can, for instance, decide to make a check dam over the river that passes through the village so that, under extreme conditions, there is reserve water available for the villagers. The cost of the check dam, however, varies with height, and the choice of height will, in turn, depend on upon how much water the villagers intend to store. This choice is also important because the dam height also has a trade-off with the costs and the land allocation for the storage site. If decisions are made based on the projections of climate change in a specific scenario, then choices are clear because the assumptions of the scenario are guiding the choice of the adaptation strategy. The optimal strategy here is sensitive to the assumptions that are made. If future climatic conditions do not turn out to be extreme, then employing irrigation techniques like those of drip irrigation and the like may be more efficient. If we reverse the process and explore the range of plausible future climate conditions that a specific adaptation technique can deal with, we are considering the robustness of the strategy against future climate conditions. This process retains a broader range of climate uncertainty in the adaptation choice. The underlying principle is not to rely on data projections, but to design strategies that hold good for a wider spectrum of plausible scenarios (Lempert & Collins, 2007).

A problem that LDCs face is that the application of RDM to policy and project planning has become methodologically quite complex and requires the manipulation of large climate data bases. The technical capacity and computing infrastructure to implement these methods is often lacking, resulting in the need to call in international experts, or simply not address the issue of deep uncertainty at all, except in the form of a side-bar sensitivity analysis of one or two of the SRES emissions scenarios. In the final section of this chapter, we try to pull together the concepts of short- and long-run adjustments to climate change, the economic metrics used to value climate change, and the costs and benefits of adaptation with the issues of flexibility and robustness in the framework of ex-ante, ex-post planning.

RDM generally focuses on finding adaptation options and projects that are robust across a large number of climate scenarios. By implication, at least, the most robust actions may not be optimal for any single climate. In the next section, we take a different tack and look at the robustness of optimal (economically efficient) adaptation options and projects across different climate scenarios. This will allow us to use the deviations from the optimal case to measure robustness, using the economic metrics presented in Chapter 2, and further illustrated in the case studies in Chapters 3 and 4. In the process, we show more meaningfully how the concept of economic regrets can be used to measure economic losses when ex-ante guesses about the ex-post climate turn out to be mistaken.

Making Mistakes in Ex-ante, Ex-post Planning: Damages, Benefits and Regrets

This section shows how the existing economic framework for ex-ante analyses of adaptation options and projects, developed in Chapters 2 and 3, can be improved by adding the concept of economic “regrets” to those of climate change damages, the short- and long-run net benefits of adaptation and residual climate change damages. It also illustrates, through a set of simple examples, how this expanded framework can be used to inform flexible and robust adaptation choices in the face of deep climate uncertainty.

As emphasized throughout this report, the issue of robustness is primarily an infrastructure problem. Dams, highways and bridges, like many other forms of infrastructure, are sensitive to climate variability and climate change. They cost a lot of money to plan, build and maintain. Once built, it is important that they perform as designed in a wide range of climatic states to achieve the performance objectives for which they were designed. If not, the planned flow of economic services from these structures will be disrupted. Furthermore, once a piece of infrastructure is planned and built, the costs of avoiding not only repeated climate-related performance failures that are outside operational parameters, but also a single catastrophic failure are also generally quite high and, at the extreme end of the failure scale, may require complete replacement.

In the case of climate variability, where there is a steady-state climate record long enough to create fairly reliable simulations of how a structure will operate after it is built, there is always the possibility that unplanned-for climatic events and systems failures will occur for both statistical and structural design reasons. In the case of short climatic records, the key parameters of climatic distributions are less reliable, and even more flexibility has to be built into climate-sensitive structures to make them more robust to a wider range of climatic events.

However, as mentioned in introduction to this chapter, the possibility of climate change is even more extreme: the observed climate record is not steady-state; it is evolving and relatively short. This makes recent historical data very unreliable for longer term projections, until there has been enough time to establish not only the parameters of the partial and joint distributions of climate-related variables, but also their trends over time. The alternative is to use GCM and RCM projections. However, these climate projections vary widely, depending on their emissions scenarios, the combinations of GCM and RCM models used, the initial conditions, physics, and the non-anthropogenic climate-forcing sources and factors that are built into (or set prior to) the various climate models.[53] More importantly, these “inputs” into climate projections do not have any known distributions, in many cases because they are not stochastic in nature.

This is why the term “deep uncertainty” has been coined to characterize the large degree of variability between climate model projections. And this is why operational flexibility and robustness have become such important components in infrastructure planning, especially in the area of water resources (Hobbs et al., 1997; Jeuland 2009 and 2010; Jeuland & Whittington 2014; Lempert 2013; Lempert & Groves 2010; Lempert et al., 2002; Lempert et al., 2006; Mulvey et al., 1995). The more operational flexibility that can be built into a structure over a large range of climate projections, the more likely it will be able to achieve

53 See: http://www.climateprediction.net/climate-science/climate-ensembles/

the planned operational objectives. However, this comes at a cost because the most robust design will not necessarily be optimal for any single climate projection except one.[54]

The Concept of Economic Regrets

The concept of economic regrets was originally introduced, not in economics, but in civil engineering where it applied primarily to the costs and performance of infrastructure decisions, for example, about the design of dams and roads in the face of risk regarding the state of future climates, well before the development of global climate models and regional climate models (RCM). In these cases, the emphasis was designing physical structures in a way that would make them fairly robust to climate variability. As such, robustness was a design characteristic of infrastructure that measured how well it performed across a variety of different climate-driven futures. Performance could be measured in various ways, such as reliability (1- frequency of system failures), vulnerability (the magnitude of system failures), resilience (length of time to recover from a system failure), and the cost of the design(s).

For this study, we define economic regrets, in terms of climate change, as an economic loss that will occur *when* or *if* the ex-ante projections of future climate states used to plan a capital project do not occur ex-post. In that case, the economic regrets of this planning "mistake" can be defined as the ex-post economic welfare loss that will occur relative to the net benefits of the best alternative plan for the climate state that does eventually occur in the future. The concept of economic regrets can be illustrated, in its most basic form, by using a 2 x 2 matrix, as shown in Table 5.8. This matrix could be expanded into a much larger one, with many different rows and columns to reflect different options for different climates, but it is much easier to explain the concept of economic regrets with this more simple matrix. Moreover, in using this matrix we assume, in contrast with RDM, that all of the welfare levels shown in the matrix represent the result of economically efficient short- or long-run adaptation.

The two rows in Table 5.8 represent two capital adaptation projects, denoted as A0 and A1, for example, two different water supply reservoirs with different storage capacities. These are ex-ante choices that have to be made before the future climate is known with some degree of certainty. The two columns represent ex-post (future) climate states, the current climate in the future, C0, and climate change, C1. The values W(A, C) indicate the net present value of economic welfare for water users for each of the four option-climate choices.

Table 5.8.[55] Ex-Ante, Ex-Post Planning Matrix for Two Capital Projects and Two Future Climate States.

Ex-Ante Adaptation Option Choices (A)	Ex-Post Climate States	
	Current Climate (C0)	Climate Change (C1)
Option 0 (A0)	W(A0, C0): long-run equilibrium for C0	W(A0, C1): short-run equilibrium. A0 is fixed
Option 1 (A1)	W(A1, C0): short-run equilibrium, A1 is fixed	W(A1, C1): long-run equilibrium for C1

54 This assumes that ex-ante planning is being done with an optimization model and that there are no multiple optima. See the Appendix to this chapter.

55 One notable feature of the example shown in Table 5.8 is that there is no Base Case. An existing practice can easily be added without changing the framework.

W(A0, C0) in the upper-left cell is the net economic welfare choice if C0 continues on into the future and A0 is planned and built in the very near future. Correspondingly, W(A1, C1) in the lower-right cell is the optimal (economically efficient) net economic welfare if the climate changes to C1. In other words, Option 0 is the best choice for Climate C0, and Option 1 is the best choice for A1. Both choices can be viewed as being in long-run equilibrium with their respective climate states according to the framework developed in Chapter 2.

Given deep uncertainty about the future climate, planners may not be able to see very well into the future, and if this is the case, they can only adjust partially in the future through short-run adaptation. As a result, the welfare values W(A0, C1) in the upper-right cell and W(A1, C0) in the lower-left cell represent the highest net economic welfare levels that can be attained through ex-post, short-run adjustments due to mistaken ex-ante choices about the ex-post climate. In the case of W(A0, C1), Option 0 is selected ex-ante, but climate C1 occurs ex-post. In this situation, the reservoir capacity will already be fixed by the previous choice of Option 0, and the reservoir owner-operator can only adjust the variable inputs, for example, by changing reservoir operation. Therefore, W(A0, C1) < W(A0, C0). The same situation holds true for the case of W(A1, C0), where Option 1 is selected ex-ante, but C1 occurs ex-post. In that case there is excess reservoir capacity, and in many (but not all) cases, W(A1, C0) < W(A1, C1) after short run, ex-post adjustments. If no further adjustments are technologically and economically feasible, then W(A0, C1) - W(A0, C0) and W(A1, C0) - W(A1, C1).

If it is not technologically possible and economically feasible[56] to make another long-run adjustment in the future to conform to the ex-post climate realization, and the two mistakes cannot be corrected, it is at this point that economic regrets come into play. In the case of the ex-ante choice of Option 0, when climate C1 occurs ex-post and no further long-run adjustment occurs, W(A0, C1) - W(A1, C1) is a measure of the economic losses associated with the ex-post economic regrets of not choosing Option 1 ex-ante. In the case of the ex-ante choice of Option 1, when climate C0 occurs ex-post and no further adjustment occurs, W(A1, C0) - W(A0, C0) measures the ex-post economic regrets of not choosing Option 1. *As such, economic regrets measure the economic loss associated with guessing the wrong future (ex-post) climate in the ex-ante planning stage.* Economic regrets can also be measured when the economically feasible level of further long-run adaptation is incomplete in the sense that the maximum net benefits of further adaptation cannot be achieved.

If, on the other hand, complete adjustment is possible (but with no further adjustment costs[57]), then W(A1, C1) - W(A0, C1) and W(A0, C0) - W(A1, C0) represent the highest levels of the net benefits of further long-run adaptation to the ex-post climate in the two cases. If there are further adjustment costs in the future, as is much more likely, there will be a reduction in the values net adaptation benefits. In this case, anything in-between no adjustment, W(A0, C1) and W(A1, C0), and full adjustment, W(A1, C1) and W(A0, C0), will result in some level of economic regret due to the technological and/or economic infeasibility of fully achieving the welfare levels W(A1, C1) and W(A0, C0). However, there also will be some net benefits of adaptation; otherwise, no additional ex-post adaptation would be undertaken.

This takes us back again to Chapter 2 and the issue of short- versus long-run decisions in economics. In ex-ante infrastructure planning that accounts for the effects of climate change and deep uncertainty, the long-run infrastructure design needs to incorporate short-run flexibility so that, once a climate-sensitive

56 Economically feasible means in these two cases that the maximum economic regret can be reduced, but at the time same time the maximum net benefits of further adaptation cannot be fully achieved, including adjustment costs.

57 This is a very strong and unlikely assumption. It is introduced purely for the sake of exposition.

structure has been planned and built, it can avoid a wide range of climate change damages under different climate scenarios. Such designs would involve lowering short-run climate change damages by building short-run operational flexibility into the design of infrastructure in order to avoid further investments to recover from making mistakes about ex-post climate states. If this not the case, then hopefully it will also be possible to design alternative long-run adaptation options that accomplish the same objective with lower long-run adjustment costs in making further investments to adjust to these mistakes.

An Example: Looking for Robust Water Resource Adaptation Options that Minimize Climate Change Damages

One way to assess the flexibility and robustness of a specific structure in the planning stage (ex-ante) is to simulate the future (ex-post) operation of alternative structural designs using a linear or non-linear programming model to maximize the net present value of the sum of consumer and producer surplus over alternative climate projections over time.[58] Each structural design will be optimal for one climate scenario (or possibly more, if there are multiple optima), while the other designs will be sub-optimal. One can then arrange the results in a matrix that displays the net present value results for all of the designs for all of the scenarios to evaluate how well each option performs in the short- and long-run.

We show how this can be done using a 2 x 2 matrix example like the one in Table 5.9. However, in the example, the matrix has been evaluated using a mathematical programming model to evaluate the performance of alternative infrastructure options.

The example involves the case of a small catchment on which two "newly empowered" farmers want to develop two fully irrigated farms in a semi-arid region. Both farmers are planning to produce exclusively for the market, and both farmers will be "price takers", which means that their production levels are so small that they will not affect market prices. Both farmers plan on diverting water from a yet to be built small, jointly owned storage reservoir that will be fed by a small stream. The reservoir fills during the run-off season, and the two farmers withdraw water later, in the dry season, part of which coincides with the irrigation season, when they must water their crops. They want to plan and construct the farm reservoir so that it is optimal for existing run-off patterns. The farmers are assisted in their planning by a farm extension agent, an agricultural economist from the provincial government. The agent has good information about the relationship between the current climate and stream flow over a long period. However, he also has information about just one climate scenario, which projects that the climate will change from the existing climate (C0) to a different climate (C1). The agent does not know how reliable the climate scenario is, nor does he have any information about the probability of occurrence of either climate. However, he wants to see how it will affect the optimal storage capacity of the small reservoir the farmers plan to build. Under C1, the available information suggests that stream flow is expected to decrease in the run-off season and increase during the dry season, as well as become more variable during both seasons.

The planning problems that the agent faces are:

1. To plan the economically optimal capacity of the farm reservoir and the associated net present value of the returns to water for each farm and the capital cost of the farm reservoir under both the current and projected climates.
2. To be safe, he also wants to know in the planning stage what will happen in the future if the farmers decide to build a reservoir that is optimal for one of the climates, but the other climate occurs. In

58 The timing of the infrastructure alternatives can also be included as an element of their design using non-integer programming.

particular, he wants to know how robust the reservoir designs are under both climates. This, he reasons, is important because, once a reservoir has been planned and built (ex-ante) that is optimal for one climate (ex-post), it could be very costly for the farmers to rebuild it in the future to be optimal if the other climate occurs (ex-post), for which the reservoir was not designed.

3. How to present this information to the farmers so that they can make rational choices consistent with their private economic interests.

The agent has at his disposal an optimization model that allows him to maximize the net returns to water by both farmers less capital costs over a thirty-year period for both long-run (reservoir capacity is unconstrained) and short-run (reservoir capacity is constrained by previous decisions) situations.[59]

In the example that follows, A0 and A1 will represent the reservoir capacities that are optimal for C0 and A0 respectively. To obtain the value of the objective function corresponding to W(A0, C0) in Tables 5.8 and 5.9, the model is run for a Base Case climate by setting the mean and standard deviation of the run-off probability density function to their appropriate values and by treating storage capacity as an unconstrained, decision variable (A0) greater than zero. To obtain the value for W(A1, C1), the mean and standard deviation of the run-off probability density function are set so as to reflect adverse climate change, and the storage capacity (A1) is treated as an unconstrained variable. These net welfare values represent the highest net economic return to water for each climate when reservoir capacity is optimal for the two different climates. To obtain the value for W(A1, C0), the adverse climate scenario for run-off is re-run, but storage capacity is now constrained at its value determined for the Base Case. The same strategy is adopted to determine the value of W(A1, C0). The model is run for the Base Case climate run-off, and the storage capacity is constrained at its value determined in the adverse climate scenario (A1). The same approach can be used if the example is expanded to three or more climate projections and three or more reservoir capacity options to reflect the increasing number of climate projections that are becoming available. It can be further expanded into a two-stage stochastic programming model to account better for climate risk and uncertainty, using subjective probabilities and distribution parameters for the stochastic streamflow inputs. However, this lies well beyond the scope of this report.

The initial net welfare results for the numerical example, using the optimization model described in the appendix to this chapter, are shown in Table 5.9.

Table 5.9. Net Welfare Results for the Example 1 (Following Table 5.8).

Ex-Ante Adaptation Option Choices (Reservoir Capacity)	Ex-Post Current Climate (C0)	Ex-Post Future Climate (C1)
	Stream Flow (mean, std. dev.) (80, 10)	Stream Flow (mean, std. dev.) (40, 40)
Option 0 (A0) Storage Capacity (SCAP) = 998 m^3	W(A0, C0) = €754,300 SCAP = 998 m^3	W(A0, C1) = €507,500 SCAP = 998 m^3
Option 1 (A1) Storage Capacity (SCAP) = 1220 m^3	W(A1, C0) = €748,400 SCAP= 1,220 m^3	W(A1, C1) = €516,750 SCAP = 1,220 m^3

59 The structure of the optimization model is outlined in the appendix to this chapter. The parameters of the crop production functions, crop prices, variable costs and the capital cost functions for the storage reservoirs are all hypothetical. All the numerical results that follow were generated using the model described in the appendix.

The decision model output is arranged as in Table 5.8. But there is one important difference: the value of W(A1, C0) is greater than W(A1, C1), indicating that considerable short-run adjustments are possible if the climate does not change, for example, by planting higher value crops under more intensive irrigation. The columns indicate the two climates, C0 and C1, while the rows in the table indicate two "adaptation" options:

1. A0: plan and build the reservoir with an ex-ante storage capacity of 998 m^3, based on the expectation of climate C0, or
2. A1: plan and build the reservoir with an ex-ante storage capacity of 1220 m^3 on the expectation of climate C1.

The numerical results for the various choices described above are presented in Table 5.10.

Table 5.10. Example 1 Results for Climate Change Damages, Net Benefits of Adaptation, Economic Regrets and Residual Climate Change Damages for Two Climates and Two Adaptation Options.

Economic Metrics	Option 0	Option 1
Max Net Welfare	W(A0, C0) €754,300	W(A1, C1) €516,750
Climate Change Damages	W(A0, C1) - W(A0, C0) - €246,800	W(A1, C0) - W(A1, C1) €231,650
Net benefits of further Adaptation (if full adjustment is feasible)*	W(A1, C1) - W(A0, C1) €9,250	W(A0, C0) - W(A1, C0) €5,900
Economic Regrets (if full adjustment is not feasible)*	W(A0, C1) - W(A1, C1) - €9,250	W(A1, C0) - W(A0, C0) - €5,900
Residual Climate Change Damages	W(A1, C1) - W(A0, C0) - €237,550	W(A0, C0) - W(A1, C1) €237,550

**The possibility for less than full adjustment (at zero cost) in the event of further adjustments is not considered. In that case, no further long-run adjustments are possible without project redesign.*

Table 5.11 contains some additional information that is available from the model to compare the two options.

Table 5.11. General Results for the Example 1 from the Optimization Model.

Parameters/Variables of Interest	A0		A1	
	C0	*C1*	*C0*	*C1*
Average annual run-off (m^3 /yr) wet dry	 819 491	 492 862	 819 491	 492 8.618
Storage capacity (m^3)	998	998	1,220	1,220
Capital cost (€)	34,980	34,980	49,360	49,360
Max net returns to water (€)	754,300	507,500	748,400	516,750
Average annual water use (m^3/yr)	867.8	555.7	875.6	550.1
Average annual marginal return to water (€/m^3/yr)	20.175	27.75	20.54	27.17

The most dramatic results for this example have to do with the character and magnitude of the climate change damages. These are associated with the short-run impacts of climate change and subsequent short-run operational adjustments on net welfare if ex-post climate diverges from that for which an option was planned. If Option 0 is implemented ex-ante, on the expectation that C0 will occur, but the ex-post climate that occurs is C1, then climate change damages are equal to a loss of - €246,800, or about 33 per cent loss of net welfare. If, on the other hand, Option 1 is implemented ex ante, on the expectation that C1 will occur, but the ex-post climate that occurs is C0, then climate change damages (benefits in this case) will represent a net increase in welfare (a benefit) equal to €231,650, a net welfare gain of about 45 per cent. From the standpoint of just short-run adjustments to the impacts of climate change, Option 1 is superior to Option 0 because, even without making a further long-run adjustment, Option 1 produces much higher average net welfare under both climates and is less than one percentage less than the net welfare W(A0, C0).

Bringing long-run adjustments into the picture does not change the previous conclusion. If Option 0 is selected ex-ante, based on the expectation of C0 when C1 occurs ex-post, long-run adaptation does little to reduce climate change damages. If increasing reservoir capacity is technically and economically feasible,[60] then the net benefits of long-run adaptation are only €9,250, or about a 4 per cent reduction in climate change damages. If not, then the economic regrets of not being able to adapt are equal to a loss of - €9,250. If Option 1 selected ex-ante, based on the expectation of C1 when C0 occurs ex post, and it is feasible to reduce storage capacity, the net benefits of long-run adaptation are only €5,900, a less than 1 per cent increase relative to the net benefits produced by the change in climates. If this is not feasible, then the economic regrets of not being able to adapt are equal to a loss of - €5,900.

But if Option 1 is the most robust of the two option choices under both climates, with or without a further long-run adjustment of reservoir storage, there is still something of an issue: the residual climate change damages for Option 0 are - €237,550, while the residual damages (benefits) for Option 1 are +€237,550. So, clearly Option 1 is to be preferred, as it the most robust in both cases. However, the cost of making the wrong ex-ante guess has very different implications for the residual damages for the two options. Therefore, we consider a second example with a different result that reduces this difference by placing greater emphasis on the net benefits of adaptation.

An Example: Looking for Robust Water Resource Adaptation Options that Maximize the Net Benefits of Adaptation

We now substitute a new option, Option 2, for Option 1 in an example that emphasizes the role of further adaptation to reduce climate vulnerability due to mistaken guesses about the future climate. The second example keeps the climate-driven run-off at C0 and C1. Option 2 combines the possibility for a change in reservoir storage capacity with an option that reduces water losses due to evaporation, seepage and the transpiration of aquatic plants. This has the effect of increasing effective storage without large increases in storage capacity. We also changed the irrigation method for Option 2 to drip irrigation and more effective irrigation scheduling, which, taken together, can increase yields for a given amount of water. The revised matrix is shown in Table 5.12.

60 Additional adjustment costs were not estimated for any of the examples due to a lack of data, but as previously indicated they are an important aspect of long-run adjustments to climate change that need to be considered.

Table 5.12. Example 2 - Revised Example Matrix for Two Climates and Two Adaptation Options

Adaptation Option Choices (Reservoir Capacity)	Current Climate (C0)	Future Climate (C1)
	Stream Flow (mean, std. dev.) (80, 10)	Stream Flow (mean, std. dev.) (40, 40)
Option 0 (A0) Storage Capacity (SCAP) = 998 m^3	W(A0, C0) = €754,300 SCAP = 998 m^3	W(A0, C1) = €507,500 SCAP = 998 m^3
Option 2 (A1) Storage Capacity (SCAP) = 1,022 m^3 + Reduction in Water Losses	W(A2, C0) = €694,300 SCAP= 1,022 m^3 + Reduction in water losses	W(A2, C1) = €726,100 SCAP = 1,022 m^3+ reduction in water losses

The net welfare results in Table 5.12 need a little explanation for Option 2. Adding drip irrigation plus loss prevention increases both variable and capital costs for Option 2. However, because the added measures replace some storage under C0, less capacity is needed, and capacity costs decline somewhat. The added measures are also not as effective under C0 when run-off is plentiful, as crop yields are already near a maximum under C0 for Option 2 due to high run-off. Therefore, there is a small decline in net welfare compared to the previous example. When the climate becomes drier and more variable, as in C1, the added measures allow farmers to increase their yields substantially (even with less storage capacity than in the previous example), and the gains in revenue considerably outweigh the additional variable capital costs.

The optimal ex-ante choices for the options under the two climate projections are W(A0, C0) = €754,300, the same as in the previous example, and W(A2, C1) = €726,100, which is higher than in the previous example. As before, there are two ex-post results for making mistaken ex-ante climate guesses:

- Select Option 0 ex-ante, when Option 2 would be optimal ex-post, and
- Select Option 1 ex-ante, when Option 0 would be optimal ex-post.

The results for the various metrics used in assessing adaptation options are given in Table 5.13.

Table 5.13. Evaluated Adaptation Metrics for Revised Example Matrix.

	Option 0	Option 1
Max Net Welfare	W(A0, C0) €754,300	W(A2, C1) €726,100
Climate Change Damages	W(A0, C1) - W(A0, C0) - €246,800	W(A2, C0) - W(A2, C1) - €31,800
Net Benefits of Adaptation (if adjustment is feasible)	W(A2, C1) - W(A0, C1) €218,600	W(A0, C0) - W(A2, C0) €60,000
Economic Regrets (if adjustment is not feasible)	W(A0, C1) - W(A2, C1) - €218,600	W(A2, C0) - W(A0, C0) - €60,000
Residual Climate Change Damages	W(A2, C1) - W(A0, C0) - €28,200	W(A0, C0) - W(A2, C1) €28,200

In this revised example, there are three important features in the results. First, the new Option 1 design shows higher maximum net welfare under the climate for which it was designed than the previous Option 1. As a result, the net welfare maximums, under the climates for which they were designed, do not vary as greatly as in the previous example. Second, while the climate change damages for Option 0 are the same as before, the climate change damages for Option 2 are now negative instead of positive and large. Third, the net benefits of further adaptation and economic regrets have higher absolute values than in the previous example, substantially offsetting more damage in both absolute and relative terms. Thus, the residual damages/benefits of climate change are much smaller in this case. Therefore, further long-run adaptation is economically far more effective in reducing vulnerability to climate change than in the previous example, provided further adjustment is possible and adjustment costs are low. This has the potential effect of making a better case for Option 0 than in the previous example.

Since we are focusing on the net benefits of further adaptation in Tables 5.12 and 5.13, it is worth pointing out that, if it is economically feasible to adjust completely from W(A2, C1) to W(A0,C1) or from W(A2, C0) to W(A0, C0) through further adaptation, then economic regrets in either or both cases will be zero. Cases of economically feasible but incomplete adjustment would yield negative values smaller than the maximum value of the economic regrets shown in Table 5.13. Of course, this would also be the case with the previous example.

However, taken together, the two examples illustrate several important points about using different decision criteria to evaluate how robust and flexibly adaptation options can adjust to different climates. First of all, selecting the option which minimizes climate change damages over a wide range of climates may not always be the best strategy, depending on the importance of the net benefits of further adaptation. The same is true for selecting an option that maximizes the net benefits of further adaptation depending on the direction and magnitude of climate change damages. On the other hand, minimization of the residual climate change damages may appear, at first glance, to be the least ambiguous criteria for robustness, but this will also depend on the value of the economic regrets associated with the very high adjustment costs from case A0, C1 to A2, C1 or from case A2, CO to A0, C0. The latter point highlights the importance of building infrastructure projects in such a way that, when an ex-ante climate guess turns out to be wrong, either 1) it is technically and economically feasible to reduce a large portion of climate change damages through further long-run adaptation; or 2) substantial short-run flexibility is built into infrastructure projects to reduce climate change damages such that the role of further long-run adaptation becomes less important. This was the case with the first example.

So, we have a choice: either select or design the most robust option over both options by emphasizing ex-post short-run flexibility, or make both options more robust based on increasing the net benefits of additional long-run ex-post adaptation, with an attendant reduction in residual damages, but an increased risk of economic regrets if further long-run adaptation is technologically and/or economically infeasible. Which is the best approach? Ultimately, that choice depends on the risk preferences of those who receive the benefits and those who pay the costs.

Finally, the same general approach can be used for more than two final climate and adaptation outcomes. In fact, the matrix does not even have to be square: there can be more adaptation options than projected climate states. It is also not necessary to use an optimization approach to create the matrix, although it is helpful to do so because the strengths and weaknesses of different infrastructure designs are easier to track that way, and because it is likely that the “best” option, whatever the decision criteria, may also be optimal for at least one projected climate, if not more. While pairwise comparisons can be useful for untangling the effects of design differences among alternatives, it can also require a lot of effort, as the number of comparisons is equal to the product of the number of rows and columns. In that case, the initial approach would involve summing the relevant metric for each decision criterion (minimizing climate change damages, maximizing the net benefits of adaptation or minimizing the economic regrets of infeasible or incomplete further adaptation) for all climates, taking the mean value of these sums, and then applying the decision criteria to select a subset of the best options for further pairwise analysis. This would also involve taking into consideration other measures of flexibility and robustness that account for the variability of the relevant metric over all the climates for each of the selected alternatives. In doing this, it is imperative to be able to work out the adjustment costs for each option over each projected climate.

Chapter Summary

This chapter is divided in three sections. The first section deals with how uncertainty has been dealt with in literature. The second section elaborates on decision-making processes under uncertainty and moves on to elaborating traditional approaches to decision-making. The final section describes the concepts of economics regrets and its evolution from engineering to find relevance in policy decision-making for climate change adaptation. The section also presents two practical examples of robust water resource adaptation options by minimizing climate change damages and maximizing net climate benefits.

It is often convenient for decision-makers to assume that information on future climate scenarios is accurate. In practice, this information is anything but perfect due to various factors that stem from the assumptions made in scenario development. Decisions taken now have to account for future developments and therefore have to deal with uncertainty by either reducing it or managing it. Any decision based on imperfect information can reduce welfare of the society or has opportunity costs. There are scientific limits to reducing uncertainty: for example, downscaling GCMs to RCMs will increase uncertainty. Decisions cannot be put on hold until perfect information is available, and therefore decision-making under uncertainty has to be facilitated.

Traditionally, probabilistic approaches have been used to understand risks. The expected value approach uses probabilities and payoffs for decision-making. Decision theory takes a non-parametric approach to decision-making. The concepts of maximin, minimax and maximax have been elaborated in light of the risk averseness of the decision-maker. Finally, real options represent the case of the decision-maker having to value non-financial options like the option to abandon rights etc. In most of these traditional approaches, the decision-maker has a clear picture of options, pay-offs, and probabilities.

These decision-making alternatives do not adequately support-decision making under deep uncertainty where the probabilities of scenarios are meaningless and neither the future state of the climate nor the universal set of possible future scenarios is known. Robust decision-making processes help identify appropriate adaptation strategies that perform well in a wide range of plausible future climate scenarios, thereby giving flexibility to decision-makers in the form of an alternative to heavily reliance on future projections. Similar approaches for dealing with deep climate uncertainty need to be mainstreamed in economic analysis for adaptation options.

The last section in this chapter uses an optimization-based approach to explore the issue of robustness in a simple case where farmers in a developing country must decide the economically efficient level of the storage capacity for two options, one that works best under the current climate, and one that works best under climate change.

Two examples are provided to highlight two different approaches to the concept of robustness. In the first example, we presented a case where the best option for the current climate was not as robust over both climates as the option geared to climate change. The distinct difference between the options was that climate change damages were large and negative for the current climate-based option, while those for the climate change based option were large and positive. However, the difference in residual damages was very large.

In the second example, the option favouring the current climate was not changed. The climate change-based option was changed so that maximum net welfare under the climate change scenario was much higher than in the first example, but much lower under the current climate scenario.

These differences in the second example resulted in negative climate change damages and much larger net benefits of adaptation for the climate change-based option than in the first example. In addition, the net benefits of adaptation for the current climate-based option were also much larger than in the first example. This resulted in large reductions in residual damages/benefits for both options. Thus the emphasis in the results in this example was on the ability to increase the net benefits of further adaptation in the future in the face of a wrong prediction of ex-ante climate, with the attendant risk of large economic regrets if additional long-run adaptation in the future proved impossible.

As such, the two examples highlighted two different approaches to robust project design. The first example emphasized the robustness of a single option by building long-run flexibility into the climate change-based option, thereby reducing the regrets associated with additional long-run adaptation in the future. The second example made both options more robust through project designs that can be modified by additional long-run investments in the future. However, this alternative comes at the expense of greater economic regrets if additional adaptation in the future is not technologically and/or economically feasible. The comparison further illustrates how different robustness criteria can result in very different types of project design and economic welfare outcomes and risks.

Appendix to Chapter 5

The ex-ante planning model used in the analysis in the last section of Chapter 5 is a hydro-economic model (Hurd et al., 1999) of a small watershed with just two (i = 1, 2) farms and a small water supply dam, where all water ($X_{i,c,t}$) is used consumptively. This problem takes the form of finding the optimal storage level ($STCAP_{c,0}$) for two different climates $c=c_0$ and c_1 over t= 0, 1,..,n time periods:

Maximize $Z_c = \Sigma_t [\Sigma_i P_i f_{i,c,}(X_{i,c,t}) - \Sigma_i h_i X_{i,c,t}]^*(1+r)^{-t} - c(STCAP_{c,0})$ ***Equation 5.2***

S.T. $S_{c,t+1} = S_{c,t} + RO_{c,t}[C_c(\bullet)] - \Sigma_i X_{i,c,t}$ for all t, ***Equation 5.3***

$S_{c,t} \leq STCAP_{c,0}$ for all t. ***Equation 5.4***

Where:

$P_i f_{i,c,}(X_{i,c,t})$ is the crop production function for each farmer, $h_i X_{i,c,t}$ represents variable costs function for each user, $c(STCAP_{c,0})$ is the capital cost function, and

P_i = the crop price(s) for each user,

h_i = the input prices for each user, and

r = the discount rate.

Eq. 1 is the multi-period objective function, running over all n time periods. It accounts for the present value of the short-run net returns to irrigation of each farm in each period ($P_i f_{i,c,}(X_{i,c,t}) - \Sigma_i h_i X_{i,c,t}$) less the capital cost of the storage reservoir $f(STCAP_{c,0})$, which is incurred in period 0.

Eq. 2 is the mass (water) balance for the storage reservoir to ensure that water storage in each period, t+1 ($S_{c,t+1}$) is equal to the water storage level in period t ($S_{c,t}$), plus run-off into the reservoir in period t ($RO_{c,t}$), minus the consumptive water use of both farms in period t ($\Sigma_i X_{i,c,t}$). Furthermore, run-off in each period is treated as a function of climate, $RO_{c,t}[C_c(\bullet)]$, but the exact relationship between climate and run-off is not specified in $C_c(\bullet)$. For the current climate, run-off values can be obtained from a probability density function fitted to historical data or simulated using a stream-flow or rainfall run-off model. For climate change scenarios the problem is more difficult, since probability distributions for multiple ensemble runs from GCMs and RCMs do not exist for reasons already stated. In that case, one can either

- assume that these runs are generated by a stochastic process or by stochastic inputs to deterministic process, and fit one or more distributions to ensembles data and simulate run-off from the fitted parameters
- assign subjective probability distributions and their parameters to ensembles data and simulate run-off from the subjective parameters.

In either case, there are a potentially bewildering number of probability distribution-parameter combinations that could be used to simulate the effects of different climates on run-off. The prevailing practice at the moment is to assume uniform distributions.

Furthermore, run-off is assumed to be a function of the mean (μ_c) and the standard deviation (σ_c) of the climate driven, run-off probability density function $C_c(\mu_c, \sigma_c)$.

Finally, Eq. 5.3 is the storage capacity constraint that requires that water storage in each period is never greater than the capacity of the reservoir.

The strategy for running the model to produce the results in this chapter is discussed in the text of Chapter 5.

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Dike, long wall or embankment built to prevent flooding at river near Wat Chaiwatthanaram, Ayutthaya historical park, Thailand

6. Summary and Conclusions

John MacIntosh Callaway, Jr. and Prakriti Naswa

Summary

In the Introduction to this report (Chapter 1), we indicated that it represented an effort to weave together a strictly economic definition of adaptation to climate change with a theory of economic adjustment to exogenous environmental changes, focusing on the role of short- and long-run adjustments, and with the need to develop the technical capacity of local experts to estimate the benefits and costs of adaptation in their own countries.

In Chapter 2, we put forward a purely economic definition of adaptation to climate change as "*the adjustments in resource allocation that economic agents make in their consumption, production and investment decisions to avoid the economic losses, or to increase the economic gains, due directly or indirectly to the effects of climate change*". We also took issue with the distinction between autonomous and planned adaptation, since from an economic perspective virtually all adjustments made by economic agents to exogenous changes in the environment are planned, and we substituted it with a distinction between short- and long-run adaptation. Following up on this distinction, we presented a graphic analysis to show how adaptation could be decomposed into short- and long-run adaptation. We further emphasized the importance of investing in technological changes that would allow variable inputs to be better substitutes for capital. Incorporating short-run, operational flexibility into long-run adaptation investments (primarily infrastructure) in this way would reduce the vulnerability of structures to climate change by improving their operational robustness over a much wider range of future climate states. Finally, this chapter introduces and defines the economic metrics used in the rest of the report to account for the various benefits and costs of adaptation, namely climate change damages, the net benefits of adaptation and residual climate change damages.

Chapters 3 and 4 focus on the need to develop the technical capacity of local experts to estimate these benefits and costs in their own countries. Chapter 3 presents a simplified, bottom-up approach to estimate the adaptation metrics in local case studies. This approach is hard to define, because it can take many forms. It involves using locally available data to outline the main technical and cost characteristics associated with different soft or hard technologies and/or management strategies to avoid current and/or future damages from climate change and/or climate variability. Damage functions taken from available impact models or studies are used to determine the effects of climate change/variability on the output of the economic activity that is affected by climate and/or on fixed and variable costs. Marginal economic values (prices) for outputs are based on currently observed prices and can be varied through sensitivity analysis. All this information is organized into an accounting framework on a spreadsheet, such that different climate scenarios can be used to simulate the effects of climate on production and on an appropriate net welfare metric under different adaptation options. Finally, Chapter 3 illustrates the use of this approach through two hypothetical examples: switching from conventional to conservation tillage; and adopting rainwater harvesting to supplement rain-fed agricultural production due to reduced and more variable rainfall in the Central Rift Valley of Ethiopia.

This simplified bottom-up approach is taken further in Chapter 4 with four more examples covering the adoption of conservation tillage in Tanzania, increasing the size of protected areas in the Brazilian Amazon to offset deforestation, protecting coastal population centres from cyclones in the Bay of Bengal, and using beach nourishment to increase tourism revenues in a hypothetical LDC setting. All of these adaptation activities yield both development- and adaptation-related benefits. As such, the beach nourishment example shows why and how it is necessary to add a conventional benefit-cost analysis to the analysis of adaptation-related benefits and costs.

Chapter 5 covers the topic of "deep uncertainty". Deep uncertainty arises out of ambiguity, disagreement among analysts and decision-makers, and a lack of information regarding the models that describe interaction among the system's variables, probability distributions representing uncertainty and assessments of the appropriateness of alternative outcomes (Lempert et al., 2006).[61] We show how current risk-based methods for resolving uncertainty are difficult to employ in the case of deep climate uncertainty, where a fast-growing suite of climate projections lack any empirical or theoretical basis for assigning probabilities. As a result, Robust Decision Making (RDM) developed by the Rand Corporation is making growing inroads into the use of stochastic methods to resolve deep climate uncertainty. RDM is an analytic framework that stands conventional ex-ante planning on its head by first identifying and developing adaptation strategies, analysing the robustness of these strategies over a number of projected climate outcomes, and then, in typical cases, iterating the strategies or infrastructure designs in concert with stake-holders and policy-makers to find the most acceptable solution. Finally, Chapter 5 illustrates an approach for dealing with deep uncertainty that focuses squarely on mistakes in forecasting ex-post climate states during the ex-ante planning process. The results of these mistakes can be broken down into higher than expected climate change damages and/or lower net benefits of adaptation. We show how decision-makers can avoid the economic regrets associated with these mistakes and introduce greater ex-ante robustness over multiple climate projections by one of two means: through reductions in climate change by means of improved operational flexibility in ex-ante infrastructure designs, or through improvements in the net benefits of additional, ex-post, long-run adaptation to climate change, for example, by building projects so that robustness features can be added on to an existing capital investment.

Conclusions

This report has four main conclusions:

1. Economists in many Developing Countries Need to be Brought up to Speed in the Economics of Climate Change

It has been the experience of the authors of this report that, while they have encountered many well-trained economists in the poorer developing countries, these economists have not always understood how their skills can be applied to climate change. As a result, we have seen a number of cases where multi- and bilateral organizations prefer to "import" international experts to conduct such studies, often without making any contact with local experts. Part of the rationale for this study was to show how existing data bases could be used by local experts to estimate climate change damages, the net benefits of adaptation and residual climate change damages using a simplified bottom-up approach, as was done in the case studies in Chapter 5.

61 Lempert, R. J., Groves, D. J., Popper, S. W., & Bankes, S. C. (2006). A general, analytic method for generating robust strategies and narrative scenarios. *Management Science, 52*(4), 514 – 528.

However, this is certainly not enough. More importantly, multi- and bilateral donor and aid organizations needs to make more effort to refocus the excellent underlying skills of economists in LDCs to conduct sector and national-level studies of the benefits and costs of adaptation to climate change, as outlined in this report, using locally available data and models.

2. More Clarity is Needed in Defining the Economic Benefits and Costs of Adaptation

There has been a great deal of confusion regarding the definition of the economic benefits and costs of adaptation to climate change, especially in policy documents and discussions, but less so in the economic literature. Part of this has to do with the existing definitions of adaptation, most of which contain elements that are implicitly, but not explicitly, consistent with economic theory. We have argued that there is nothing really new in the economics of adaptation and, in that regard, it can be regarded as the actions taken to adjust (adapt) to exogenous changes, directly, to climate or, indirectly, to the effects of climate change on the physical environment. These adjustments typically involve the reallocation of resources in consumption, production, and investment, leading to benefits and costs.

What these benefits and costs are called is not as important as their conceptual underpinnings. The definitions we have used from Chapter 2 onwards, namely climate change damages, the net benefits of adaptation (adaptation benefits less the cost of the real resources used to adapt to climate change) and the residual climate change damages capture in fairly rigorous terms the most relevant welfare aspects of adaptation. The same definitions could just as easily apply to the economic benefits and costs of, say, air and water pollution.

The application of these metrics is shown in a consistent way in the case studies presented in Chapter 4, using a simplified bottom-up approach.

3. Distinguishing Between Short- and Long-run Adaptation is Important

The distinction between short- and long-run adaptation has not received much attention in the economic literature. Non-economic distinctions between different types of adaptation, such as autonomous vs. planned adaptation and anticipatory vs. reactive adaptation, are confusing (if not irrelevant) in terms of economic theory, and not particularly useful to apply to the economics of adaptation. In place of these distinctions, we suggest that the distinctions between short- and long-run adaptation and between private and public adaptation is far more important to the economics of climate change.

In Chapter 2, we have shown in a fairly stylized version that, given a permanent climate shock on the production side, there are two paths of adjustment from this shock: the short-run path, involving only a change in variable inputs; and the long-run path, involving a change in both capital and variable inputs, with the latter yielding the highest net benefits of climate change and the lowest residual damage costs. Nevertheless, this is shown only for deterministic cases.

In the face of deep climate uncertainty, things may change.

4. More Emphasis Needs to be Placed on Decision-making Under Deep Climate Uncertainty in Economic Studies

Methods for dealing with deep (climate) uncertainty have not received very much attention in the applied literature on the economics of adaptation, particularly in the case of climate-sensitive infrastructure projects involving large capital outlays and long lifetimes. In Chapter 6, we argue that Robust Decision Making (RDM) methods need to be brought into the mainstream of economic analyses of adaptation benefits and costs, as traditional risk-based methods are not appropriate for quantifying the expected consequences of adaptation.

This conclusion is particularly relevant to the distinction between short- and long-run adaptation in the case of investments in climate sensitive infrastructure. Faced with the large range of climate outcomes shown in various ensemble and RCP studies, as well the difficulties in assigning probabilities to these outcomes, economic agents of all kinds may be hesitant to make long-run, ex-ante adjustments. This is due to the low likelihood that the ex-post climate realization will match the ex-ante climate expectation. On the other hand, if variable inputs are not good substitutes for capital, the welfare loss associated with a short-run decision could also be quite high. We argue that an important element of the solution to this dilemma is to build short-run ex-post flexibility into long-run ex-ante decisions, such that infrastructure investments are more robust to a wide variety of climate outcomes.