Aggregating, presenting and valuing climate change impacts

vivideconomics

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FINAL REPORT
February 2011

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Executive Summary

Disclaimer

This report was commissioned by the Department of Energy and Climate Change in spring 2010. It was prepared by Vivid Economics and the views expressed are those of Vivid Economics. DECC may or may not endorse the views found in this report.

Outline terms of reference

The Government was seeking a fresh approach to aggregating, presenting and valuing the multiple impacts of climate change resulting from different levels of greenhouse gas emissions, taking into account:

— how impacts vary over time and world region, for given GHG emissions pathways;
— how these impacts can be valued considering their temporal and regional distribution;
— how these valued impacts can be suitably expressed to reflect the likelihood and distribution of each impact, given the uncertainties in predicting and valuing specific impacts for any given time period and region.

The principal aim of this study was to present a clear and easy to understand representation of the impact of different greenhouse gas emissions pathways. The authors attempted to do so, but were unable to prepare a picture on a consistent global basis from the rich diversity of pieces of evidence available.

Findings

Governments and researchers wish to be able to value, aggregate and present the impacts of climate change in a convincing, clear and transparent way to decision makers and to the public. The authors hope that this report may assist them by reviewing a large body of literature to find the ways in which climate impacts are being and have been estimated and shows the scale of those impacts. It then sets out suggestions for improving the presentation of impacts for the benefit of decision makers and a wider audience. The intention is to open up new areas of debate on choice of metrics, not to close them down.

There have been a great many climate change impact studies, and there have been some thorough reviews of them before this report, in particular, the Intergovernmental Panel on Climate Change's Fourth Assessment Report. This review may be distinctive in its aim, which is to consider how to improve the presentation of impacts.

This review reveals the limitations of some of the metrics in use today, including some of those with high profiles and in wide circulation, such as percentage GDP losses and 'millions at risk'. They may not convey as much information about the scale and distribution of impacts, or socio-economic context of climate change impacts, as might be ideal now or may be desired in the future. This may make them less compelling. Other metrics, in use today sometimes in other contexts, may be better-suited for that purpose, but it may not be easy, and in some cases, it may not be feasible in the context of climate change, and in the short term, to collect the analytical data from which to construct them. Hence it may be desirable to hold open a wider debate about the use of metrics.

This report selects some metrics from the best of the current crop of them and suggests some others to create a suite of metrics which focuses attention on three areas: (i) monetised impacts, (ii) impacts on the life chances of the vulnerable poor, and (iii) impacts on ecosystems. Monetised impacts have the advantage that they may be summed across space, time and states of nature to give an aggregate impact that can be compared with the costs of mitigation and adaptation. The impacts on the life chances of the vulnerable poor can be summed in a similar way, and here a framework of functionings, already familiar to the development policy community from the annual reports of the United Nations Development Programme, might be used. These metrics of life chances cover health, education and access to basic services. A question is how feasible it might be, especially in the short term, to introduce these metrics for climate change impacts. Creating metrics of the climate change impacts on ecosystems may also be infeasible in a short timescale. One way forward is to divide impacts on biodiversity into species- and biome-related effects, and ecosystem services, using well-established frameworks for measuring extinctions and mean species abundance. However, for measuring ecosystem service levels there are not the same well-established, comprehensive frameworks and in some instances there are no measurements at all.

The estimation of these impacts varies in difficulty and reliability. This report reviews the methods used. In doing so, it considers the extent to which monetisation is desirable and feasible for each metric. For impacts on goods traded in markets, market prices provide a reliable and valid estimate of economic value. For non-market impacts where value can be derived indirectly from market prices, it may also be possible to elicit sufficiently robust economic values. However, for impacts where value can only be elicited from surveys of hypothetical willingness to pay, there might be difficulties obtaining reliable and valid estimates, especially at the global level. The result is that for impacts on market activities such as agriculture, water supply and energy, monetisation may be feasible. For health, non-monetary aggregation of health states may be feasible (e.g. Disability-adjusted Life Years or DALYs), and monetisation may also be feasible. For ecosystem services which contribute market goods, monetary valuation might be feasible in some cases, though there is a lack of reliable estimates at the current time. For impacts on the life chances of the vulnerable poor, species abundance and ecosystem non-market services, it may be best if monetisation is not attempted.

Estimation of climate change impacts is still a young science, in some areas. In particular, the modelling of socio-economic impacts has looked in greatest detail at lower increases in temperature than the science now suggests are possible. The climate models themselves concentrate on average changes in climate, with greater confidence in estimates of temperature than of precipitation, and little detail on winds. This means that there is high uncertainty about the variance of climate around mean temperature and precipitation levels. It is this variance which causes disastrous events such as coastal inundations and tropical cyclones. Even greater uncertainty than this surrounds the likelihood and severity of catastrophic, discontinuous shifts to new states of the global climate system, caused for example by collapses in ice-sheets or a halt in the thermohaline circulation.

Uncertainties are also inherent in the estimation of the impacts of given climate states on people and ecosystems. For example, the deprivations of the vulnerable poor are augmented or diminished by the uncertain state of economic wealth and the quality of institutions in many decades' time when the impacts of climate change occur. These uncertainties in climate science and in the estimation of socio-economic impacts combine.

Thus uncertainty plays a significant role in the overall assessment of impacts. This is a challenge for decision-makers, who have a standard set of assessment tools for dealing with certain, i.e. sure, events, and can also, like insurers, compute the costs and benefits of action where risks, i.e. probabilities, are known. However, when the probabilities of climate change impacts are poorly understood, the appropriate decision-making framework is less clear.

In this context of 'ignorance', standard decision theory tends to propose two simple rules, which differ in the degree of caution they imply. 'Maximin' chooses the policy option that results in the least worst case. 'Minimax regret' chooses the policy that minimises regret, in terms of the difference between the best and worst cases. The metrics used to describe impacts might be put to use within this framework in the future.

The findings of this report are applied to a set of climate change impact indicators for a number of sectors, such as health, poverty and ecosystems. When the impacts of climate change are viewed in these novel ways three conclusions become apparent. Firstly, the impacts of climate change are revealed to extend far beyond monetised global GDP loss cited in some key policy decisions. Secondly, climate change might have a significant impact on other global causes for concern, for example poverty, as climate change may reduce people's capability to overcome deprivation. Finally, the burden of climate change falls predominantly on the developing world, increasing the deprivations already faced by the majority of the world's population.

A compelling presentation is placed in context, and explained relative to alternative scenarios and level of certainty. Some recent examples fall short of this ambition in one way or another.

The current evidence base does not yet cover all important states of the world, including temperature rises greater than or equal to 4°C, extremes of temperature, precipitation and wind, discontinuous catastrophic changes such as ice sheet collapse and ocean circulation cessation, as well as significant losses in ecosystem functioning.

A number of steps can be taken in the short term, which might improve impacts estimation, valuation and presentation in the medium to long term. Some of the research priorities are immediately obvious. They include health impacts, poverty indicators, ecosystems, extreme weather events and agriculture. They span climate science on precipitation, extreme and catastrophic events, CO_2 fertilisation in agriculture, ecosystem service valuation, the determinants of the functionings of the poor, and the effect of extreme events on health and agriculture.

In addition, there may be a case for greater coordination, strategic planning and funding of research efforts, in order to accelerate the rate of improvement in knowledge, for example, along the following lines:

— establish a coordinating vision and framework for the socio-economic impacts to be assessed and the scenarios over which impacts will be assessed;
— identify gaps in the evidence base and precursor data, open this assessment to

comment, and publish its findings;

— facilitate the coordination and comparison of further impacts estimation work.

There may also be merit in publishing a regular impacts assessment report, in the same vein as the UNDP human development report, using a set of relevant and meaningful indicators.

In conclusion, this report illuminates the current methods and difficulties of impact valuation, aggregation and presentation. Lessons are learnt from the literature and relevant, targeted impact indicators are suggested. In particular a suggestion is made that health, poverty and ecosystem impacts are presented alongside any economic valuation. With regards to uncertainty the suggestion is to draw from a suite of decision rules appropriate to the level of uncertainty and the decision maker's degree of caution. Our work is drawn together through proof-of-concept indicators that illustrate both what is feasible and also the scale of climate change impacts when viewed in a fresh light.

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1 Introduction

1.1 Terms of reference

The Government was seeking a fresh approach to aggregating, presenting and valuing the multiple impacts of climate change resulting from different levels of greenhouse gas emissions, taking into account:

— how impacts vary over time and world region, for given GHG emissions pathways;

— how these impacts can be valued considering their temporal and regional distribution;

— how these valued impacts can be suitably expressed to reflect the likelihood and distribution of each impact, given the uncertainties in predicting and valuing specific impacts for any given time period and region.

The original specification of work envisaged three phases, the first phase was to be the collation of impacts from the AVOID programme and other relevant sources and the presentation of them in an aggregated, non-monetised form. The second phase was to be the monetisation of impacts assessed in the AVOID programme, and the third phase was to be a consideration of uncertainties including extreme events in order to assign a range of valuation estimates resulting from different levels of greenhouse gas emissions.

The specification asked for:

— devise a set of metrics that allows complex, heterogeneous impacts to be presented coherently, and which, ideally, is understandable to the public;

— review of studies which attach valuations to climate-related impacts;

— review of literature that may be relevant in the following areas: natural environment, agricultural economics, insurance and risk assessment and health economics;

— ascertain key impacts for key regions and time periods, aggregating where necessary, using a business as usual scenario and one abatement scenario, across a range of sectors;

— take into account uncertainty with associated probability weights;

— take into account extreme events, socially contingent events and irreversible tipping points;

— devise how to express these aggregated impacts as a welfare loss to people in the regions.

Among the difficulties encountered were the differences in metrics, scenarios, approaches and assumptions across the literature, and in some aspects, an absence of information. It soon became apparent that parts of the evidence base needed to deliver the specification of work were not available.

Hence, the team embarked upon a pragmatic exercise to identify a suite of metrics relevant to the audience, to ascertain to what extent these metrics could be populated with current evidence and how they might be framed in a manner that aids interpretation. The team found some promising metrics available, which might offer significant improvement over some of those used previously. They are, however, quite demanding in terms of the data and analysis that may be involved in their production.

The team addressed the question of presenting uncertainty. The investigations made clear the sources of uncertainty and showed that uncertainty is and will remain for the foreseeable future a feature of significant climate impacts estimation. Despite the pervasiveness of uncertainty over impacts, the team found a lack of data across well characterised states of the world. As a result the presentation of uncertainty was not possible. The emphasis shifted to questions of how to support decision-making given uncertain information. An answer to this question, it was thought, might indicate how the estimates could be presented and where priority might be given to further work.

Having made some progress on the matter of uncertainty, the team set about to identify the gaps in evidence that prevented them from fulfilling the original terms of reference in respect of the suggested metrics. This turned out to be a major exercise in itself. It took the study into specialist fields and led them to make suggestions which now ought to be the subject of review by experts in these fields.

Thus, when it came to presenting estimates of impacts and their valuation, the team selected from the evidence that was available and applied it to the framework of metrics they had proposed. It was possible to build up a partial picture, and this confirmed in which areas further information would be needed if the metrics are to be put into use. While the team had hoped to be able to present ranges of uncertainty in the estimates, they were concerned that the presentation could be misleading, because the individual studies from which they were drawing each individually had explored only some of the sources of uncertainty. For this reason, the presentation of impacts does not set out the ranges of impacts that might occur.

1.2 Structure of the report

The material in this report is divided into sections, each with its own theme. There is supporting background information in the appendices.

The report begins with a review of metrics that have been used recently in published climate impacts work, in section 2. It is supported by appendix 1, which displays a selection of some of the best and most well-known recent graphics showing impacts information.

The use of these metrics and ways in which they can be presented is set out. This is combined with a discussion of the appropriate use of monetisation and aggregation to form the content of section 3. It prepares the way for an analysis of what data is needed. The much narrower approach to impacts taken by the insurance industry is briefly summarised in appendix 2.

Section 4 goes on to extend the range of metrics used, suggesting that familiar metrics from the health, economic development and biodiversity fields could be co-opted, and illustrates how the results might look. More detail on the framework for poverty analysis is provided in appendix 3.

These suggestions are put to the test in section 5. A summary of current estimates of climate impacts is presented using the range of metrics and presentation devices discussed earlier. Background information on the sources of estimates is set out in appendices 4 and 5.

Another aspect of information content is addressed in section 6: uncertainty. The handling of uncertainty in decision-making informs a view in this section on the value of information on extreme outcomes. It is supported by additional material on uncertainty in decision-making in theory and in practice in appendices 6 and 7.

This leads to a set of recommendations for further work to improve the evidence base, laid out in section 7, and summarised in tables at the end of the section. The summary tables are supported by more detailed analysis in appendix 8.

The conclusions, in section 8, contain the team's reflections on the whole study.

The bibliography can be found at the end of the appendices, and is divided into topic areas.

1.3 Acknowledgements

We gratefully acknowledge the support of the steering group and project manager at DECC throughout this project, and their expert colleagues, especially for their patience as the work navigated through this complex field. The peer reviewer, whose thoughtful comments led to many improvements, was a pleasure to work with. Thanks also go to members of the AVOID team who gave us insights into the achievements of current work and areas of ongoing endeavour early in this project.

2 Current metrics of impact

Key messages

Estimates of the global impacts of climate change are reported in studies of single sectors and in integrated assessments which encompass all sectors.

The results are reported in a wide range of metrics, many of which are sector specific. In addition, some integrated assessments monetise impacts across several sectors and express the results as a proportion of gross domestic product.

It is sometimes not possible to compare estimates across studies either between sectors or within a sector because the metrics are incommensurable. Sometimes this is of necessity and sometimes it is not.

Some of the metrics used are difficult to interpret because they do not give a measure of scale. There are usually alternatives available which do contain a measure of scale. These are not always used.

2.1 Introduction

This section sets out the metrics reported by a number of leading studies which examine climate impacts and adaptation. The sources include a sample of sectoral studies, the UK's Avoiding Dangerous Climate Change (AVOID) programme, recent work by the World Bank and the IPCC, and discussion papers leading up to COP 15.

The metrics used in the health, ecosystems and flooding climate impacts literature are described first. Then metrics from the AVOID program and the development and health literature follow.

Metrics from the insurance industry and also global climate impacts modelling are discussed in appendix 2. In addition, the presentation of the metrics is described in appendix 1.

2.2 Metrics reported in sectoral studies

This sub-section reports the metrics used in studies which report climate change impacts on individual sectors, and covers health, ecosystems and flooding.

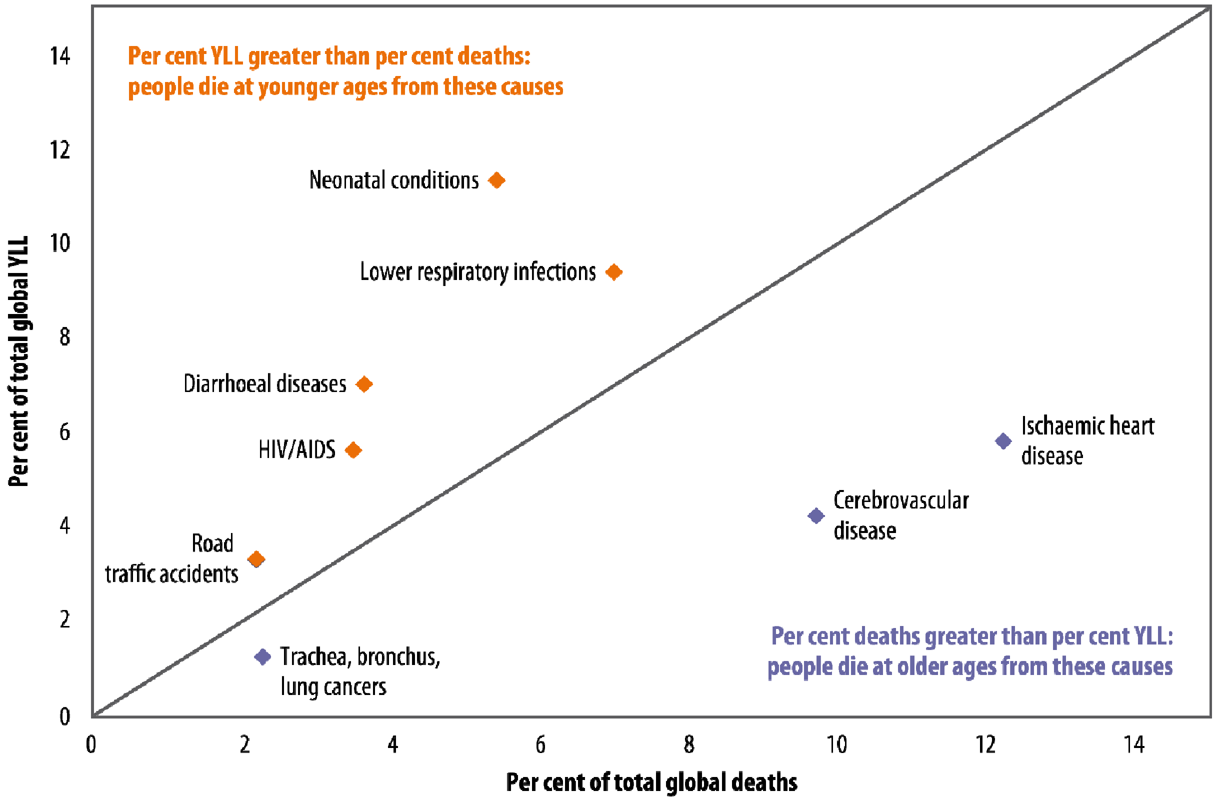
2.2.1 Health

Health impacts tend to be aggregated using non-monetary indicators. These present two key challenges: the identification of an appropriate life expectancy against which to judge mortality, and the selection of weightings for types of morbidity. At a minimum it is important to go beyond the number of deaths to calculate years of life lost, as figure 1 shows. Even more instructive is to incorporate morbidity and so report impacts on health state, where a health state describes an individual's health relative to perfect health.

Human health has many aspects. The World Health Organisation uses the definition 'health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity', IHC (1946). It is widely recognised as useful to value health impacts if the scarce resources available for health services are to be allocated well. Since simple measures of mortality and disease incidence do not adequately describe the burden of disease, richer metrics have been developed.

Health-adjusted Life Years (HALYs) is a generic term for measures of population health that collapse both morbidity and mortality into a single metric. Mortality is measured as a departure from health-adjusted life expectancy (HALE), which is the length of healthy life a person can expect. Morbidity is described by an index of health-related quality of life (HRQL), which is measured on a scale of zero, perfect health, to one, death. QALYs, quality-adjusted life years, and DALYs, disability-adjusted life years, are two types of HALYs.

Figure 1 A comparison of percentage of years of life lost to percentage of deaths reveals the importance of communicable diseases



Source: The Global Burden of Disease 2004 update (2008)

QALYs have tended to be used nationally for the purpose of cost-effectiveness assessments, for example by the UK's National Institute for Clinical Excellence, and for cost-benefit analysis and impact assessment, for example, by the UK Department of Health. DALYs have tended to be used internationally, primarily in the World Health Organisation's Global Burden of Disease studies. The advantage of DALYs is their global application, so they are used here.

DALYs express the impacts of disease in terms of a departure away from an ideal global standard length of healthy life. They were pioneered by the World Health Organisation's (WHO) Global Burden of Disease (GBD) 1990 study; they are the sum of two components, Years of Life Lost (YLLs) and Years Lost due to Disability (YLDs).

YLLs describe mortality; they are simply a measure of death before standard life expectancy. Standard life expectancy in the GBD 2004 is 80 years for males and 82.5 years for females; this standard is applied globally and reflects the highest life expectancy observed in the mid-1990s. The application of a global standard life expectancy reflects a strong commitment to equality over space; it is also a point of difference from QALYs, which tend to use the actual life expectancy of the population under consideration. YLDs describe morbidity with disability being interpreted as a departure from optimal health. They use a disability weight for each health state; these weights reflect a health state's location along a continuum from perfect health, a score of zero, to death, a score of one. The weights do not communicate any information about a person's quality of life (over and above the effect of morbidity being investigated) or the value of people to society. The weights are determined by numerous, geographically diverse, group valuations, using focus groups, often a mix of experts and non-experts, openly deliberating the impact of a disease on health until they reach a consensus.

In contrast to the equal valuation of DALYs over space, DALYs over time are not valued equally. The Global Burden of Disease study discounts health impacts in the future and also gives non-uniform weights to impacts across age groups; not all health impact assessments make these normative choices. The GBD applies a discount rate of 3 per cent in order to mirror cost-benefit practices. Non-uniform age weights place a lower value on the quality of life years lost in early and later years of life.

The use of non-uniform age weights reflects arguments that human capital peaks in early adulthood. It also expresses a detectable broad social preference for years of early adulthood over other years of life.

Using a 3 per cent time discount rate and non-uniform age weights has a significant impact on the DALY value of a life lost. For example, a male death in the first year of life is valued as a loss of 33 DALYs while a male death in the 20^{th} year of life is valued as a loss of 35 DALYs. In contrast, an undiscounted and uniformly weighted metric would, given a male life expectancy of 80 years, value the former death at 79 years and the latter death at 60 years.

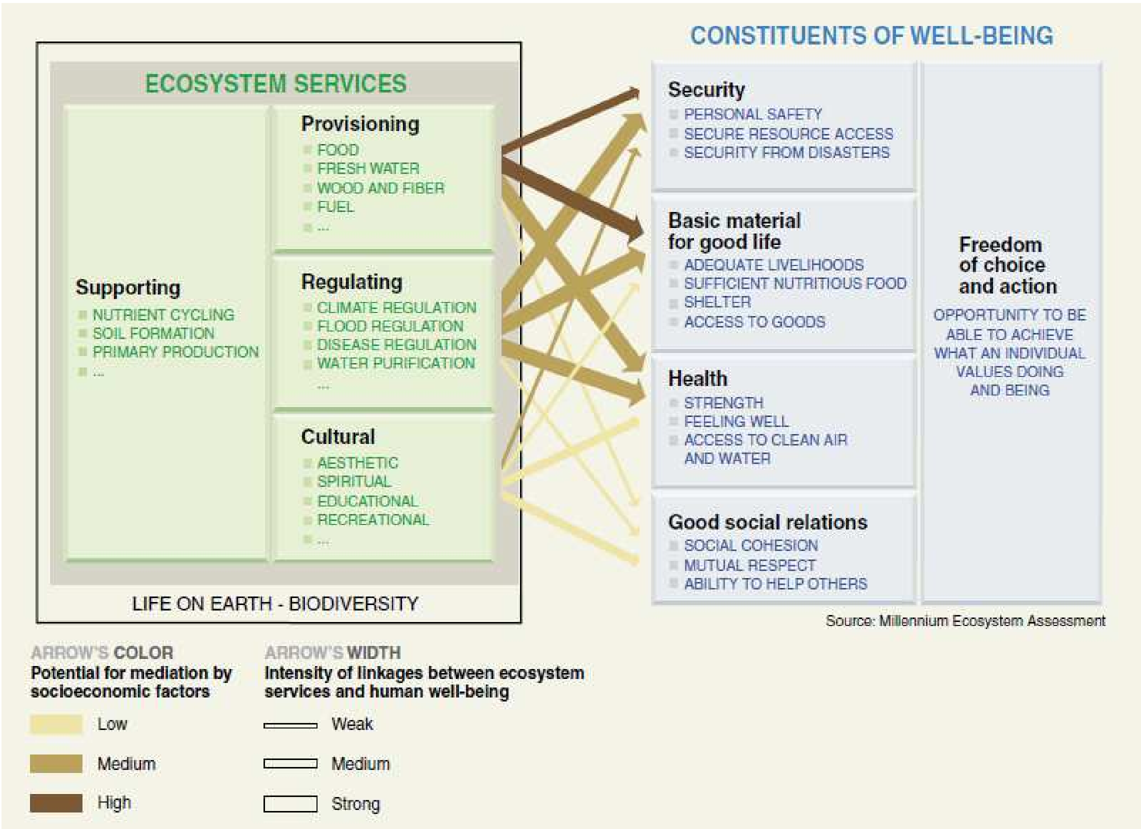
Despite the demanding normative and data requirements of DALYs, its two key strengths are that it is a global, cardinal metric across all types of morbidity and mortality, and that it has an intuitive interpretation, in so far as a DALY is a departure from an ideally healthy life.

2.2.2 *Ecosystem Services*

The value of ecosystems in relation to human well-being has a strong conceptual framework and the Millennium Ecosystem Assessment (MA) is a source of best practice in this field.

Ecosystems provide a flow of services that contribute to four constituents of well-being: security, basic material for life, health and social relations. There are four categories of ecosystem services which relate to these four constituents of well-being. **Provisioning services** deliver society with basic materials and contribute to our health and resource security. Examples are food, fibre, fuel and fresh water. **Regulating services** protect us from the vagaries of the environment, contributing to our security, health and social cohesion, as well as ensuring that basic materials are accessible; examples of these are climate, flood and disease regulation and water purification. **Cultural services** primarily improve our health and social cohesion, through aesthetic, spiritual, educational and recreational services. Finally, **supporting services** underpin the three types of services described above, and include nutrient cycling and soil formation. These indicators are all measures of instrumental worth, that is, they have value in the fulfilment of societal needs. In addition, ecosystems may be considered to have a non-instrumental, **intrinsic** value, which means they have value independently of any service they provide to society. However, it is difficult if not impossible to quantify such value, and to separate it from the value that society may place on an ecosystem's existence.

Figure 2 The relation of ecosystem services to constituents of human well-being as mapped by the Millennium Ecosystem Assessment



Source: The Millennium Ecosystem Assessment (2005)

The Millennium Ecosystem Assessment assesses a baseline flow of services for thirteen biomes. It begins with quantitative metrics such as number of species per hectare, hectares of forest cover and tonnage of fish caught. It then measures the changes in service levels over time and attributes the cause to drivers such as over-exploitation, climate change, urbanisation and invasive species. Due to data constraints changes in ecosystem services are predominately described qualitatively in the MA. The Cost of Policy Inaction project (ten Brink et al., 2009) sets out the current state-of-the-art research into the quantification of changes in ecosystem services through a database of ecosystem service valuation estimates.

While an understanding of how service levels change is important, it is more often the case that ecosystems are transformed or degraded than it is the case that they are absolutely destroyed. For example, rainforest can be cleared to make way for farmland, exchanging genetic resource services for food services. The comparison of the value of different types of services requires a common currency, for which money, or 'total economic value' (Pearce & Warford, 1993) is often used.

2.2.3 *Biodiversity*

There are a plethora of biodiversity indicators available, illustrated by the European Environment Agency's selection of 15 headline indicators from a pool of 200 possible indicators (SEBI2010, 2007; Postnote, 2008). Of these headline indicators, a key metric is 'mean species abundance' (MSA).

MSA represents the average response of the total set of species belonging to an ecosystem to a change in their environment. It is a measure of the extent to which a driver affects the level of biodiversity in a biome. As such it describes species richness; a biome achieving an MSA score of 1 is in a pristine state, with full species richness, while a biome scoring 0 is a biome devoid of original species. It does not address species evenness, and further thought might be put into how and whether to report changes in evenness. MSA is calculated in the following way:

- the abundance of species in an ecosystem with minimal human interference is established, often using modelling techniques, and the mean level of species abundance in this case is defined as 100 per cent, which is an MSA score of 1;
- the current level of species in the ecosystem is measured and reported relative to the reference level.

Alkemade et al. (2009) provide an illuminating example of what an MSA score means: '(a loss of) 0.01 of global MSA is equivalent to the conversion of 1.3 million km^2 (an area the size of Peru or Chad) of intact primary ecosystems to completely transformed areas with no original species remaining'. This is because 0.01 of global MSA is equivalent to 1% of the area of the terrestrial globe being in a pristine state.

MSA can be compared with 'risk of extinction', which, in various forms, is the type of indicator used by a number of studies informing the findings of the IPCC's AR4. Risk of extinction is a narrower metric than MSA, although still a useful one. This is because extinction due to climate change often falls on endemic species (species that only survive in a particular biome) (Malcolm et al. 2005) as climate change reduces their unique habitat. So risk of extinction provides a local indicator while MSA provides a more general indicator of biodiversity loss. Risk of extinction may be harder to estimate than change in MSA.

2.2.4 Flooding

Flood damage divides into three categories, flooding from the sea (coastal), flooding from rivers (fluvial) and flooding from run-off (pluvial).

Coastal flooding research at a global level is dominated by use of one tool and set of indicators. The Dynamic Interactive Vulnerability Analysis (DIVA) tool was developed in 2006 (Dinas-Coast, 2006) and remains the state-of-the-art model for estimating the impacts of coastal flooding. It reports non-monetised metrics relating to the environment, such as land lost, sediment lost, wetlands lost and saltwater intrusion; and relating to society, including people at risk of flooding, and people actually flooded in a scenario. It also estimates monetised impacts, namely the cost of protection, cost of retreat, cost of wetland lost, cost of saltwater intrusion, and residual damage.

Fluvial and pluvial flood estimation is more difficult because complex local hydrological conditions of precipitation and runoff matter. As a result, global estimates of fluvial flooding are limited to geographically-broad, approximate estimates of the change in flood return periods and the number of people affected. On the other hand, at the national level, models such as those used in the UK flood foresight study (Foresight, 2004) can achieve high levels of detail and so the granularity of their indicators is greater. They report indicators such as the annual probability of inundation by area, the number of people and the number of vulnerable people within an indicative floodplain, and the expected annual economic damages for the residential, commercial and agricultural sectors.

2.2.5 *Metrics used by the AVOID programme*

AVOID is a UK research programme funded by DECC and Defra and led by the Met Office in a consortium with the Walker Institute, Tyndall Centre and Grantham Institute (Imperial College). The programme contains a number of work streams, including research using a simple climate model (i.e. MAGICC) to estimate the probability of increases in global mean temperature accompanying a given trajectory of greenhouse gas emissions. In this report the focus is the coupling of temperature projections from climate models (MAGICC, as well as the complex climate model HadCM3) with models of the impacts of climate change in defined sectors: water resources, sea level rise, crop suitability, health, fluvial flooding and ecosystems. The results from these models are reported in a set of metrics, listed in table 1. This report examines only the work pre-dating November 2009.

These metrics are drawn directly from the physical model data, in combination with socio-economic and biophysical information, for example, population density and crop growth. It can be seen from table 1 that many of the changes are reported as the proportion of receptors (people or cropland) exposed to an increased or reduced risk of an event, such as a flood or altered suitability for crops. Parry et al. (2001) use a similar set of metrics to tell a story about the 'millions at risk' from four types of impact.

These metrics are not in physical or economic units. In order to convey the magnitude of an impact they would have to be converted into measures of outcome that are cardinal. For example, the water resources measure in AVOID assumes that people whose water runoff falls below a $1000m^3$/capita/year threshold, and those already under the threshold whose runoff decreases by more than one standard deviation from the 30-year average, suffer water stress. This gives no sense of how climate change has impacted these people relative to other factors, nor does it describe how acute the water stress suffered might be.

Projections of wind, needed for storms, and rainfall, an excess (the lack) of which gives floods (droughts), are thought to be less accurate than those of average temperature (Arnell, personal communication). AVOID, like most other global impact modelling, concentrates on predicting the impacts of average changes in temperature and precipitation, and not the severity and frequency of the most extreme short-duration weather events such as storms.

Table 1 Metrics reported by AVOID

Metric	Level of measurement	Dimensional?
number of people whose water runoff decreases or increases more than one standard deviation from 30-year average, i.e. more than 5 to 10 per cent	cardinal	yes
proportion of people at risk of flooding whose flood risk increases or decreases	cardinal	no (dimensionless)
percentage change in annual flood risk	cardinal	no
proportion of cropland whose suitability increases or decreases by more than 5 per cent	cardinal	no
percentage change in production of selected crops	cardinal	no
index of vulnerability of countries to a change in their aquatic provisioning services due to climate change	ordinal	yes
change in cooling-degree-day demand and heating-degree-day demand (person degree-days)	cardinal	yes
heat-related deaths per 100,000 population due to climate change	cardinal	yes
five levels of concern for European species, based on climate-related change in area of habitat	ordinal	yes

Source: Vivid Economics and AVOID key findings document, 2009

AVOID research covers a range of global mean temperatures. Probabilistic modelling with the MAGICC model is intended to quantify the risk of large amounts of warming, up to and beyond 5°C. However, the range of global mean temperatures explored in linking climate model output with the sectoral impacts models is narrower; generally up to 4°C.

The AVOID results, like those of the economic Integrated Assessment Models described in appendix 5, are most useful in the preparation of global aggregate impact estimates and in showing inter-regional variation in impacts. They do not possess the necessary small-scale geographical detail to be used in planning adaptation.

The AVOID programme could be extended to cover ecosystems outside Europe, catastrophes and health impacts other than heat-related deaths, none of which has been in the scope of work to date.

2.3 Metrics employed in development and health

The attributes of human well-being affected by climate change are also affected by many other non-climate factors. Naturally, these attributes are the subject of study outside the climate change field, and this body of work offers experience in the use of relevant metrics and presentational techniques.

One of the main sources of material is the development field. Within this field, Sen's (1999) work on capabilities and freedoms as a framework for thinking about human well-being has been implemented by the UN Development Programme and aspects of it have been combined into an index which is published regularly within the UN Human Development Report. This Human Development Index selects metrics of adult literacy, life expectancy and income levels as the three most important determinants of well-being among low income people. While Sen noted the benefits of employment, employment status is not explicitly incorporated in the UNDP's index.

This development work is particularly relevant to climate change impacts, since it is designed for people on very low incomes, and these people tend to be more vulnerable to climate change impacts wherever they are exposed to them. The application of this framework to climate change is discussed in more detail in section 3.7, and the use of capability oriented indicators is described in section 4.4.

The health field offers another pool of experience to tap. Here, there is a sophisticated understanding of morbidity resulting from disease or malnutrition, and of life years lost (for example see WHO, 2008). These metrics are linked to epidemiology of disease, and the effects of malnutrition and disease are diminished by effective preventative measures and treatments which are well-understood. The impacts of climate change fit easily into this field since they modify the range and density of disease vectors, cut access to sanitation and clean water supplies, and cause malnutrition. The links between precursors, such as disease vector density or calorific intake per day per person, and morbidity and mortality, have in many cases been studied, although still present a source of uncertainty.

The metrics used in the health literature to aggregate morbidity and mortality effects, such as forms of health-adjusted life years, are well-developed and can be used to explain the scale of climate change impacts. Their application in sectoral studies so far is discussed in section 2.2.1 and our suggestions for presenting these metrics are described in section 4.2.

A final field, economics, contains the tools to measure impacts on income, such as GDP per capita, and means of aggregating it across countries, such as at purchasing power parity. It raises the issue of income equality and uses the ratio of incomes at different centiles as a metric to make comparisons over time and space.

3 Principles of aggregation, monetisation and context-relevance

Key messages

Impact information is consumed by policy makers, the international development community, treasuries and multi-lateral funding agencies and the public, among others. Their needs and interests may differ.

In order to make complex and unfamiliar impacts more comprehensible, they may be placed in a context which reveals their relative scale. Familiar metrics may be used wherever possible, and aggregation may be made at meaningful scales. This is sometimes done and sometimes not done in impacts studies.

Monetisation is not always feasible, and may be used only where valid and reliable, and in all cases not to the exclusion of non-monetary metrics; unless full monetisation is the aim.

Monetisation may not be valid and reliable when applied to changes in biodiversity and changes in the well-being of the poorest people. Here, alternatives are available.

For those on a very low income, a framework of capabilities and functionings might be used to capture impacts. An example is the multi-dimensional poverty index (Alkire & Santos, 2010).

When aggregating over time, populations or risk, the way in which consumption (money) is converted to social welfare can have significant affects on the results. The use of sensitivity analysis and expert guidance is advisable.

3.1 Introduction

This section opens by identifying the key audiences of climate change impact indicators. Then ways of enhancing the meaning of metrics are discussed, which focus on issues of context, monetisation and aggregation. To resolve arising issues in poverty, a capabilities-based framework is recommended.

3.2 The audience and use to which information is put

There are at least three principal audiences to whom the design of presentational material might be directed.

The first audience is the domestic and international mitigation policy community. For this group, the key concern is the appropriate level and division of mitigation action, informed by the scale and distribution of damages. This group is likely to be interested in global aggregate impacts, and the concept of mitigation as insurance in minimizing regret from uncertain severe outcomes. It might also find the marginal cost of additional emissions helpful in setting appropriate incentives to avoid carbon emissions.

This audience may find it helpful to see the impacts presented in aggregate, and in payoff and regret tables, and they may wish to see irreversible effects reported separately, such as loss of species.

The second audience is development agencies and the international development community. This audience's mission is to protect the vulnerable and to steer economic development along the most beneficial course. They might wish to understand the relative importance of climate change impacts across sectors within a region, and their absolute impact on vulnerable groups. They are likely to find the interaction between economic growth and climate change impacts of great interest. For these reasons, this audience will wish to see the presentation of the spatial and sectoral distribution of impacts, and to understand the effects on the poor at a household level and in aggregate. They might appreciate a selection of indicators and structure of presentation that mirrors their other work on economic development and health improvement.

A third audience are the national treasuries and multi-lateral funding agencies. These bodies will be keen to understand the pattern of costs and benefits over time and might wish to identify who pays and who benefits, both from mitigation action and adaptation. This would help them to form a view about how much financial resource to commit over time. For them, national aggregate figures will be helpful in planning budgets and arguing for shares of international assistance, and they might be interested in monetized and market impacts above others. They might also use this information in an international context to work out the pay-off matrices for collaborative and non-collaborative action.

The public are an audience whose interests span those of all three specific audiences identified above. The public require a presentation of the big picture, which is provided by aggregated and monetized figures, to understand the scale of climate change. Impacts can be made relevant, and here the same indicators that the development community are interested in, such as health impacts and household level analysis, could anchor the case for climate change in the public's imagination. Finally, the case for action is communicated to the public. This may be best presented through an insurance lens, as the concept of insurance is familiar to the public and a wide-spread aversion to ambiguity is well-documented.

3.3 Ways of enhancing the meaning of metrics

Climate impacts are complex and unfamiliar. Part of the complexity is that they span multiple dimensions: (i) different elements of individual and societal well-being, (ii) different states of the world, (iii) different times and (iv) different locations in space. They may be aggregated over large ranges on any or all of these four dimensions. This makes it difficult to judge how large the estimates of impact really are, a judgement which decision makers need to be able to make.

Several strategies can be used to render the complex and unfamiliar more comprehensible. First, there is the use of context. Part of the creation of context is to place an impact alongside another familiar cause of similar impact, showing how large the impact caused by one driver is compared with the other. For example, species extinction due to climate change can be compared with species extinction due to expansion of built areas. This can be done both at a point in time, and relative to trends. The other part of the creation of context is to describe the state of the world in which the impact occurs, and this means the development of scenarios. For example, health impacts can be compared against scenarios of the future disease burden, or future life expectancy.

Second, there is the use of familiar metrics. This might involve the use of existing, well-recognised indicators, and it might also mean showing the impacts in a familiar unit, for example, as a fraction of household income.

Finally, an appropriate level of aggregation might assist understanding. In particular, it may be better not to aggregate together fairly certain estimates with those carrying very wide uncertainty bounds when considering the insurance analogy in a decision. Similarly it might be difficult for a decision maker to weigh up the validity of an aggregate figure which comprises impacts with easily-measurable market values and those for non-market goods drawn from hypothetical valuations.

3.4 Limits to the reliability and validity of monetisation

Non-market impacts, such as a loss of life or decline of cultural services from an ecosystem, lack a common numéraire. This means that the relative importance of these impacts cannot be described easily, nor valued, for example how much malnutrition are the cultural services from an unspoiled countryside worth?

Monetisation of non-market impacts provides a common numéraire, in the form of money, which allows such trade-offs to be made, provided the monetisation is accurate.

In theory, markets, in the absence of imperfections such as externalities, accurately reveal the relative value people place on goods and services. In the absence of a market, alternative methods can be used to ascertain the monetary value of impacts and they possess two key characteristics: reliability and validity.

Reliability is consistency in estimates across case studies. If a set of studies contains a wide range of values for the same non-market good (controlling for reasonable differences), it suggests that either no consistent value exists or the method of value-elicitation has failed to find it.

Validity is a stronger requirement than reliability. It requires that estimates of non-market monetary value tend toward the true value of the good. This requirement guards against the possibility that, due to bias or a framing effect in the valuation method, a set of reliable but consistently incorrect estimates is produced. Assessing the validity of an estimate is difficult, as the true value of the good is obviously unavailable; as a result validity is often an issue for expert judgement.

If reliable and valid estimates of the monetary value of non-market impacts can be ascertained then these impacts can be monetised.

3.5 Moving from money (consumption) to social welfare

3.5.1 The utility of different levels of consumption

A further step is needed after monetisation in order to aggregate impacts globally and over time, because the utility of consumption is thought to diverge between people across time, space and states of nature. This step is included here in full because of its important influence on the aggregate totals of monetised impacts.

This divergence arises from the fact that an extra pound to a poor person has greater utility than an extra pound to a rich person. People with different marginal utilities may be partitioned in different times, for example poorer in the present and richer in the future, different spaces, for example poorer in Africa and richer in Europe, or states of nature, for example poorer in a state of catastrophic climate change and richer in a low-damage state.

This variation in the utility of consumption changes between people partitioned along the three dimensions means that consumption losses (for each region) are transformed into utility, which then allows the utility of each region to be aggregated.

The transformation is achieved by means of a utility function. The iso-elastic utility function is commonly used, for example in the IAMs FUND, DICE and PAGE. It takes the form:

$U(c): c^{\wedge(1-\eta)} / 1-\eta$

Where c is consumption and η (eta) describes the elasticity of the marginal utility of consumption.

We expect η to be positive, so that the marginal utility of consumption decreases as consumption increases. The equation shows the importance of η, which has a triple role in representing aversion to inequality in consumption over positions along the three dimensions of space, time and states of nature. A higher positive value of η reduces the marginal utility of high levels of consumption but increases marginal utility at low levels of consumption.

The use of this utility function means that if damages occur only in rich positions then the disutility of damages will fall as η increases, but if damages occur in poor positions the disutility of damages will increase as η increases; so a greater weight is given to an impact on the poor.

3.5.2 *Aggregation of utility across space and time*

The next step is to aggregate utilities using a social welfare function. A social welfare function allows explicit weighting of utility over time and, in principle if not usually in practice, over space.

If society is averse to inequality in inter-personal utility, one can use an iso-elastic social welfare function, analogous to the utility function explained above, to aggregate over space:

$$W=\bullet_{i}\, u_{i}^{\wedge(1-\gamma)} / (1-\gamma)$$

If γ (gamma) > 0, there is aversion to inequality in utility. However, in practice, assessments are almost always neutral towards inequality in utility, with gamma set to zero, so that each individual's utility gets an equal weight; this is the utilitarian social welfare function.

Nevertheless, it is common practice to apply a discount rate to the utilities of individuals in different generations. This is the rate of pure time preference, ρ (rho).

Thus the social welfare function is eventually of the following form:

$$W=\bullet_{it}\, u_{it}(1+\rho)^{\wedge-t}$$

The view that utility in the future is less valuable than utility in the present simply because it is in the future has two supporting arguments. The first, impatience, is that humans exhibit behaviour that reveals a preference for the present over the future on no other basis than the present's temporal proximity. The Stern Review takes an ethical stance on the value of impatience by assuming a value of zero, which implies that society exhibits no impatience with respect to utility. Detractors from this view argue that the rate of impatience reflects the preferences of the current generation, where there is plenty of evidence to point to impatience. The second argument, extinction risk or 'life chances', is that there is a non-zero likelihood that the individual or 'agent' will not exist in the future, which makes utility in the future irrelevant. When considering highly aggregated utility, such as global utility in the case of climate change, the agent is society, therefore the value of the extinction risk is the probability of society collapsing, which, while not zero, will be quite small and is set at 0.1 per cent per year in the Stern Review. This is in contrast to other studies, such as infrastructure project appraisals, that tend to use values between 1 and 3 per cent per year, which may be more appropriate for a smaller set of individuals.

The valuation of climate change damages is very sensitive to ρ and η. There are no correct values for either ρ or η but high values, allied to growth in per-capita consumption, produce a high discount rate that can reduce the present value of climate damages significantly. The Stern Review found that increasing ρ from 0.1 per cent to 1.5 per cent, while keeping η equal to 1, reduced the present value of business-as-usual climate change by ~70 per cent.

The effect of changing η is ambiguous. Increasing η has the effect of raising aversion to inequality in consumption over time; since in most climate impact studies consumption grows over time, this is equivalent to raising the discount rate and future consumption losses are given less weight. At the same time, increasing η raises aversion to inequality in consumption over space; since the impacts of climate change are highest in relative terms in poor countries, this increases the value of these impacts. Finally, increasing η raises risk aversion, and, all else being equal, climate change impacts increase risk around consumption so the valuation of these impacts increases.

The Stern Review found that increasing η from its standard value of 1 to 2 in a 'high-climate' scenario would depress the present value of business-as-usual climate change by ~70 per cent, but an increase of η from 2 to 3 would restore the present value to its level when η was 1. The three IAMs reviewed in appendix 5 use values of η between 0.5 and 2.

η also influences the impact of equity-weights on valuations. The introduction of equity-weights at standard values of η can increase the valuation of damages by 25 per cent (Fankhauser & Tol et al. 2009) or higher (Antoff et al. 2009). In a utilitarian social welfare function equity-weights are raised to the power of η (since there is no other weighting); therefore valuations of damage in poorer regions increase rapidly for η greater than 1.5. So, while any value assigned to the rate of pure time preference makes a clear policy statement, in contrast, the triple role of the marginal social utility of consumption can make policy views on equity opaque.

3.6 The limitations of monetisation

If it were possible to monetise impacts on all elements of well-being, then all impacts of climate change could be collapsed into a single figure, in dollars or some other currency unit. While some elements can be monetised, others cannot. It makes sense to monetise those that can be, and place them on a comparable currency basis, and present other impacts in metrics which cannot be further combined together.

The elements that can be easily monetised are marketed goods and services with no externalities. Money generates utility because it enables an individual to freely consume goods and services which are the source of utility, and relative prices reflect the well-being the goods and services generate if certain conditions are satisfied. To the extent that elements of well-being fit into this category, then consumption can be a good measure of well-being, reflecting the utility that an individual or society can acquire. It may be less accurate in circumstances of low income and lower material standards of living, or in situations where non-marketed goods are particularly important.

Other elements cannot be directly monetised, but can still be measured. For example, life expectancy can be measured in years and, with more difficulty, morbidity can be valued without monetisation in terms of quality adjusted life-years. The advantage of non-monetised measures of well-being is that these elements can be captured as accurately as possible, avoiding the uncertainty introduced by monetisation, although there is then no clear mechanism to make judgements between different sets of outcomes, as will be seen later when decision rules under uncertainty are explained in section 6.6. Furthermore, some of the aggregation practices in use to derive comprehensive measures of health are themselves questionable, such as contingent group valuation.

It may be possible to value some non-market goods, including health states and environmental goods and services, through the estimation of shadow prices. There is an extensive literature on the procedures that can be used, but the practical difficulties are considerable, and the library of shadow price estimates is rather small. The Economics of Ecosystems and Biodiversity (TEEB, 2009) and the related Cost of Policy Inaction (COPI, 2009) have begun to collate a library of shadow prices for non-market ecosystem services.

Yet there will be some elements that cannot be expressed easily in monetary terms or measured. For example, a person's state of mind or the benefits from social and family networks are very difficult to measure, let alone value and so even a non-monetised multi-dimensional approach will struggle to include them. Some climate impacts may affect elements of this type, and, for the time being, will not be properly included in the account of impacts.

Two important alternative approaches to the standard economics of welfare estimation, i.e. monetisation, were considered. One is taken forward here and the other is rejected.

The first alternative makes well-being subjective, using findings from behavioural economics (Bernheim and Rangel, 2007). This approach incorporates ideas and evidence from psychology and neurology that indicate behaviour diverges from the standard welfarist model. It allows that policies may affect preferences directly as well as via changes in income and prices, for example, by altering the decision-making process, or the use of rules of thumb used by individuals. This makes preferences endogenous to the policy. It also allows that preferences may reflect the experience of individuals; for example, well-being may be defined relative to average well-being experienced in the past rather than as an absolute metric. This means that permanent increases in wealth do not generate permanent increases in well-being.

Although there are problems with using GDP as a welfare measure, subjective well-being does not yet offer a better alternative. The non-standard models that flow from this approach have been idiosyncratic and measuring welfare directly has proven to be difficult.

While the happiness literature is clear about some conditions that are negatively associated with happiness, such as unemployment and divorce, it is less clear about how to increase it, and some argue that it is not possible. Recognising that framing effects may be particularly important, there is an opportunity for optimal framing to become a direct part of the policy process, such that policymakers can affect decision-makers' perceptions of well-being simply by the manner in which they implement a policy. However, this may have more relevance for the design of climate policy instruments than evaluation of the impact of the physical changes.

While progress has been made in applying these ideas to individual applications, it is not yet a general approach (Saez, 2007), and so it is not applied here.

The second alternative is the framework of capabilities and functionings as proposed by Sen and mentioned earlier in the context of the UN Human Development Index. This is worth explaining in more detail.

3.7 Beyond monetisation: capabilities and functionings

3.7.1 An introduction to the framework

Sen defined capabilities and functionings as follows:

> 'The primitive notion in the approach is that of functioning – seen as constitutive elements of living. A functioning is an achievement of a person: what he or she manages to do or to be, and any such functioning reflects, as it were, a part of the state of that person. The capability of a person is a derived notion. It reflects the various combinations of functionings (doings and beings) he or she can achieve. It takes a certain view of living as combinations of various 'doings and beings'. Capability reflects a person's freedom to choose between different ways of living', Sen (1992).

Under the capabilities approach, welfare can be considered as realised welfare (measured by functioning) or feasible welfare (measured by capabilities). The standard of living is measured using an information set which is much broader than utility alone.

It can be conceived as a budget set with both marketed and non-marketed goods. The functionings are the end result of choices made by individuals from consideration of their set of capabilities. Examples of functionings, or realised welfare, include 'being healthy', 'being well-sheltered', 'engaging in civil society' and 'enjoying recreational activity'. In relation to health, an individual's capabilities may include the ability to access health services and the freedom to refuse certain interventions for moral or other reasons. Similarly, in relation to recreational activity, capabilities will depend upon whether an individual has the freedom to choose from all recreational activities and whether her health permits her to do so. Different levels of utility can be derived not only from different levels of income, but from different capacities to turn income into utility (into functionings, using Sen's language).

No solution has been found to the problem of measuring capabilities. Except for a few partial attempts at reporting capabilities, the state of both theory and data collection means that functionings are the usual subjects.

The Human Development Index of the UNDP is an important implementation of this approach. Life expectancy at birth, adult literacy, educational enrolment and real GDP per capita are the functionings and metrics chosen and aggregation is through scaling and simple averaging of each functioning. There have been other applications of Sen's framework; these have included employment status, shelter, public safety and the state of the natural environment, among others, as functionings (e.g. Klasen, 2000)

We will recommend the adoption of the UNDP version of the capabilities/functionings approach, and will suggest how a version could be created for ecosystems. Before doing so the general steps involved in generating an index are set out, and mention an alternative index, since the UNDP approach is not the only one on offer.

There is no settled technique to use capabilities and functionings in public policy, so whichever approach is chosen, there will be arguments in favour and against other approaches. The absence of consensus arises because of four main difficulties in implementing the capabilities/functionings framework in public policy. The first difficulty is the selection of functionings, such as income, life expectancy, infant mortality, child death rates or malnutrition. The second is choosing how to measure them, for example, using factor analysis, scaling or fuzzy sets. The third is whether or not to aggregate them into a measure of individual well-being, perhaps using principal components analysis, if aggregation is pursued. The final difficulty is how to aggregate individual measures into a social measure, where a standard social welfare function or a poverty or inequality metric could be used, or some multidimensional analysis carried out.

Practical solutions to some of these problems have been found. The usual approach, for example in the Human Development Index, is simply to average all the functionings, but in reality it is unlikely that each functioning has an equal bearing on well-being. In the long history of the Human Development Index and of other similar indices, such as the World Economic Forum's competitiveness index, no sophisticated approach to weighting has been developed which suggests this problem is not trivial.

The next UN Human Development Report will feature a multi-dimensional poverty index. This uses ten indicators, grouped together under three dimensions, as set out in table 2.

Table 2 The structure of the multi-dimensional poverty index proposed by Alkire & Santos (2010)

Dimension	Indicator
education	years of schooling school enrolment
health	nutrition child mortality
standard of living	cooking fuel sanitation water electricity floor that is not made of dirt asset ownership

Source: Alkire & Santos, 2010

The authors of this index select minimum satisfactory levels of provision and access for each element, and define a deprivation as being a failure to satisfy this level for an indicator. They then survey the poor populations of many countries to identify the proportion of the population living with multiple deprivations.

We note another example of the framework in use. Klasen (2000) constructed a multidimensional index of functional poverty in South Africa. He chose 14 functionings, including education, income and nutrition, and constructed an index for each as well as an overall index. He found that a standard expenditure-based poverty measure was a good proxy for the overall index, but not perfect.

There is further discussion of the capabilities framework in appendix 3.

3.7.2 *Application to climate change impacts*

The capabilities and functionings framework suggests a focus on basic needs and the major determinants of well-being when measuring climate changing impacts. The deprivations resulting from climate impacts may be chronic (gradual changes) or acute (extreme events). According to Sen (1997) there are five functionings:

— access to water and food, where the impact on the extent to which nourishment capability is met is measured. The metric used could be calorific intake, and risk of malnourishment is increased by food poverty, that is food and water prices being a high proportion of household income, which may happen if food prices rise or family income falls;

— shelter and sanitary conditions, where there may be temporary or permanent deprivation of shelter and sanitary conditions due to damage to infrastructure from storms or floods, or a reduction in income preventing access to services.

— access to health care, where there are changing needs for health care in response to the prevalence of disease, malnutrition and availability of shelter and where there can be poverty of access to extant services due to low incomes, and where damage to infrastructure or sudden increases in demand can remove access to health services altogether;

— self-determination and achievement, where, for example, damage to infrastructure and to agricultural crops can increase the likelihood and duration of unemployment. A whole range of factors affecting income and provision of infrastructure can contribute to reducing educational participation for children, with consequences for literacy and impact on earning potential. Extreme weather events can destroy household assets and force migration, destroying social networks;

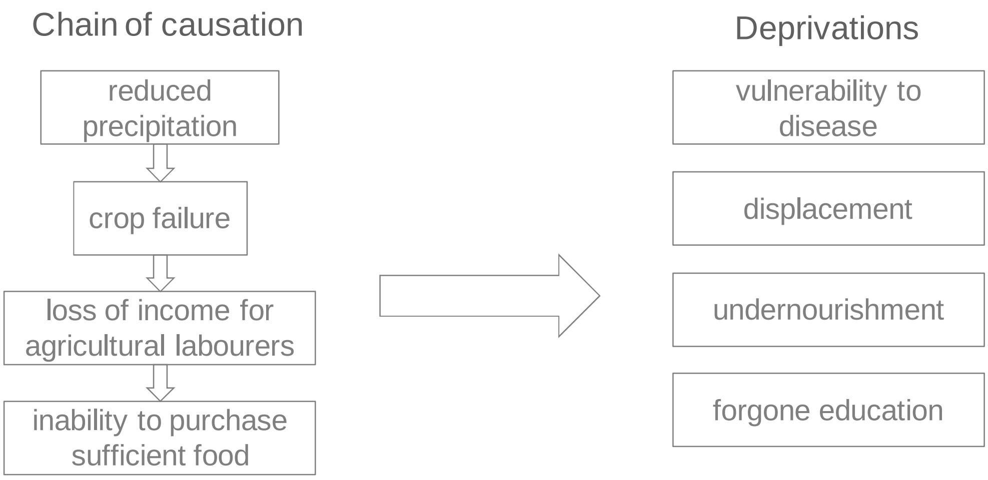
— equality, where impacts can fall differentially on households according to their level of income, because income may buy resilience to impacts, and thus the impacts can exacerbate inequality.

The multi-dimensional poverty index offers a potentially useful and improved way of reporting impacts on the vulnerable poor. Further work may be needed to ascertain the practicality of using an index in quantified analysis, particularly in the context of a range of levels of aggregation and scales.

3.7.3 The feasibility of using the capabilities and functionings framework for climate change impacts

The impacts on functionings from climate change occur through a chain of causation, such as that shown in figure 3. The quantification of these relationships is challenging and is complex. It remains to be seen to what extent the relationships can be quantified.

Figure 3 The chain of causation from physical climate change through to functionings



Source: Vivid Economics

Another difficulty is the importance of socio-economic drivers of deprivations alongside climate change. While climate change might be a major driver of inundation, in contrast, socio-economic drivers are likely to be far more important than climate change in determining the scale of disease or undernourishment. This makes socio-economic scenarios very important in determining the degree of vulnerability of populations to climate change impacts. Fortunately, methodologies exist and some scenarios of future disease burden and malnourishment have been published (e.g. McMichael et al., 2004). Unfortunately, they are not forecast as far into the future as climate impacts, tending to stop in 2030. It might be possible to extend the scenarios further, to 2050, but beyond that date, they will become highly speculative. This is one of the major uncertainties involved in the estimation of climate change impacts.

While aggregate national impact figures will show the ability of society to absorb and socialise the costs of an impact, estimates of functionings have to be made at the household level. The projection of estimates of future deprivations might be done using representative households, which are examples of groups of households most exposed to the impact. Quite detailed local information on climate impacts might be needed in order to do this. Having estimated the deprivations, they can be shown in the context of national aggregate capability figures. It may or may not be feasible to use this detailed representative household approach to generate the underlying data for global estimates of climate change impacts.

The recent World Bank adaptation study (World Bank, 2010) takes exactly this approach, making use of projections of development, and estimating malnutrition from impacts on agriculture.

Further detail on the feasibility of estimating metrics is presented in appendix 8.

4 Improved metrics and how to present them

Key messages

Some impacts can be measured adequately in money. For others, especially health, poverty and biodiversity, non-money metrics are needed as well or instead.

Health changes may be expressed at a household or individual level in units of health-adjusted life years rather than numbers of deaths alone. They can then be compared with other causes of morbidity and mortality. Monetisation might be acceptable.

Changes in income may be expressed at household level as well as in national aggregate. The number of households falling below the poverty level may also be of interest. The capabilities approach is suitable for low income households, and offers detail on multiple deprivations.

Biodiversity might also follow a capabilities approach, reporting species abundance, extinctions, and ecosystem services. It may be desirable to find a way to bring the evenness of species assemblages within this framework. Monetisation might not be acceptable other than for ecosystem services.

4.1 Introduction

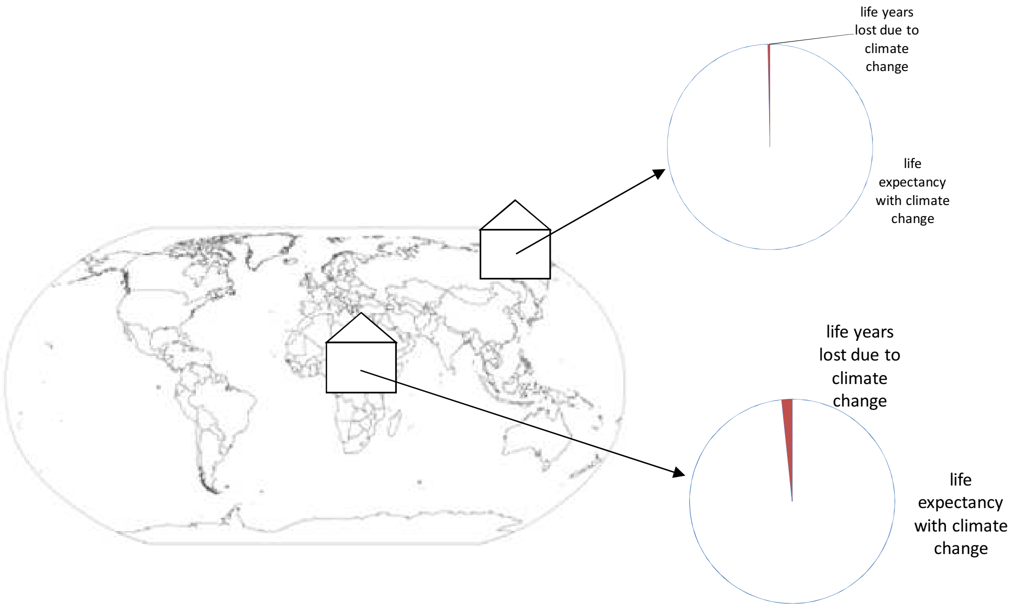
In this section the framework developed in section 3 is applied to sectors of key interest, setting out suggested indicators and ways to present them. The sectors discussed are: health, income, capabilities, ecosystems and aggregated, monetised impacts.

4.2 Health

A familiar and universal measure of life chances is life expectancy. It can be used to show the most serious deprivation of human rights, loss of life itself, and reduction in life chances, but it only incorporates mortality. A broader but less familiar metric, encompassing mortality and morbidity, is health adjusted life years (HALYs) at birth. A HALY is the generic term for a health metric that assess a person's quality of health by their proximity to a state of perfect health; disability adjusted life years (DALYs) and quality adjusted life years (QALYs) are examples of HALYs. HALYs at birth are an expectation of both the length and quality of health of a person's life in the same way that life expectancy at birth is an expectation of just the length of a person's life.

The lack of familiarity with HALYs might prevent their use alone, and the suggestion made here is that both HALYs and mortality are presented. They are suitable for global averaging and aggregation, and can also be shown for representative households by region and income level, making clear the extent to which impacts differ spatially and by socio-economic status. They are constructed using life tables, which are not available for future dates at the present time.

Figure 4 Regional variations in a key health indicator, life expectancy, can be shown for representative households, illustrative figures

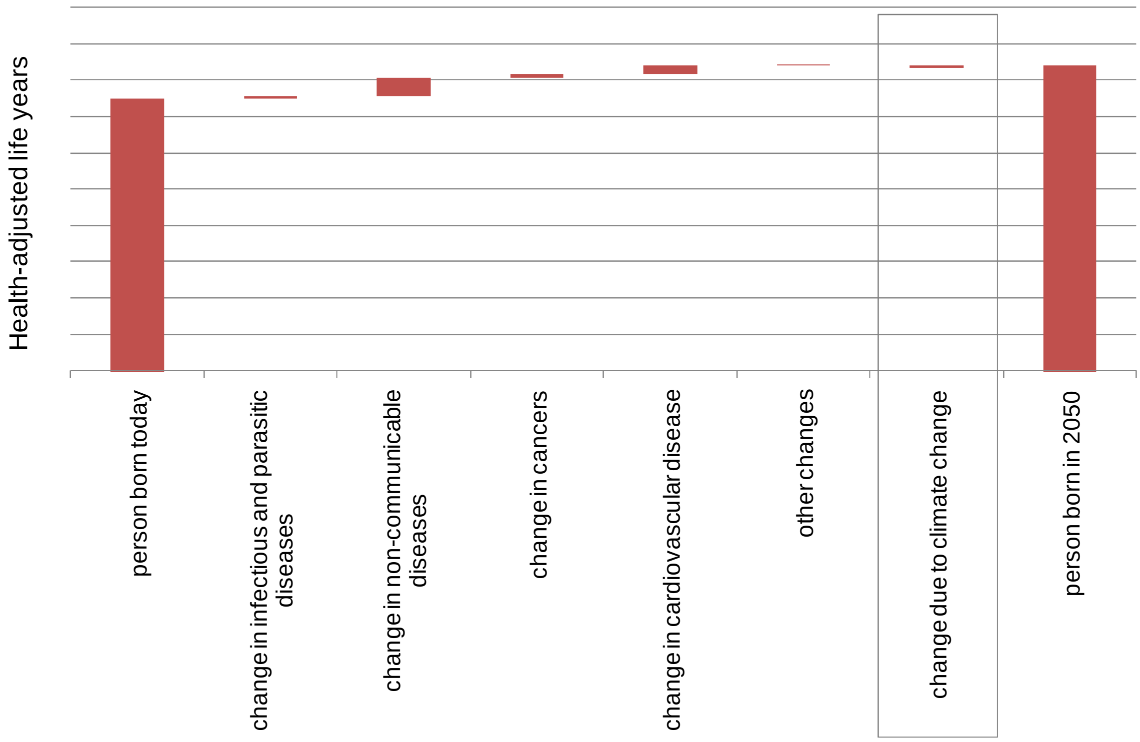


Source: Vivid Economics

To further enhance the sense of scale, the change in HALYs could be set in the context of other changes in HALYs, either other causes of loss of life years, such as disease, or trends in HALYs over time. A chart for a representative household might be produced, such as the illustration in figure 5.

Comparisons of impact can then be made between population groups, such as in the illustration in table 3, where the loss of HALYs per person is compared for vulnerable and resilient groups in exposed and unexposed areas.

Figure 5 The contribution of climate change to HALYs, for a representative household, illustrative figures



Source: Vivid Economics

Table 3 Climate change impact on HALYs, aggregated by exposure and income, illustrative figures

		Low income	High income
HALYs, per capita in 2050	Resilient to climate change		
	Vulnerable to climate change		
Population, billions	Resilient to climate change		
	Vulnerable to climate change		

Source: Vivid Economics. Note: this table is intentionally blank.

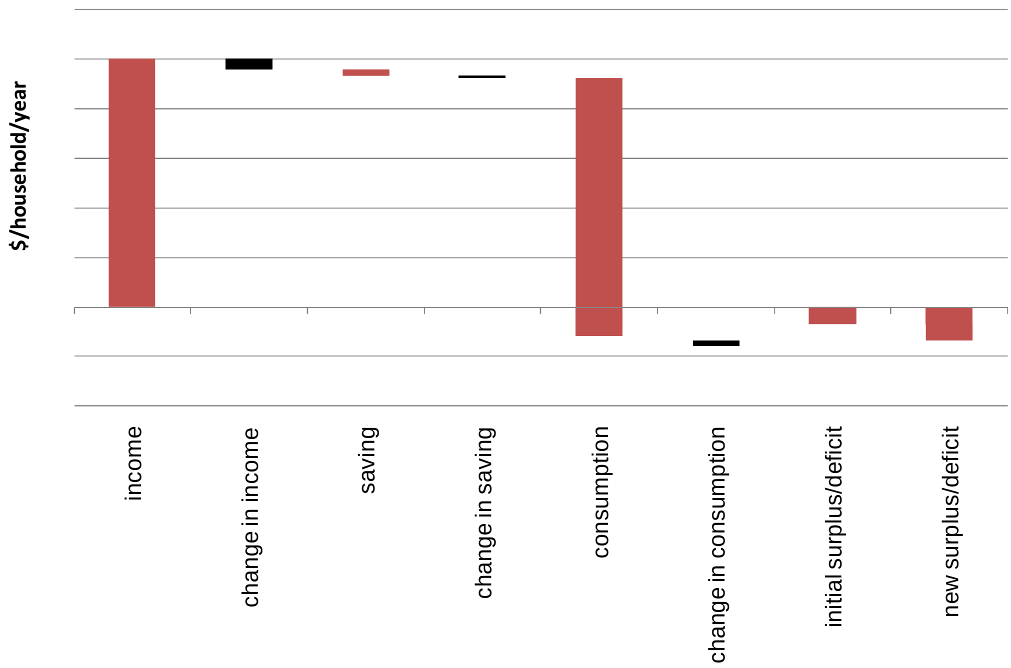
While the use of HALYs may offer a potentially useful and improved way of reporting of impacts on health, further work might examine the practicality of using such an approach. This further work might consider the availability of input data and engage experts from the health assessment field.

4.3 Income

Income lends itself to a similar approach to health. Changes in income might be presented in relation to a baseline level of income and the differences in relative impact highlighted across regions and income groups. Climate change impacts might be compared with other influences. There are considerable challenges in preparing this analysis, not the least of which is anticipating future levels and distributions of income.

The changes due to climate might be aggregated and then presented as a proportion of national economic aggregates such as Gross Domestic Product. They might also usefully be expressed as changes in household income or consumption (spending) or saving, as shown in figure 6, which is based on the Economics of Climate Adaptation Working Group (2009). For example, reduced agricultural productivity will depress the incomes of agricultural households, and investments in flood defences and additional health services could affect savings rates as consumption (spending) is diverted into investment. Consumption (spending) itself could increase if prices rise. For example, if the cost of water supply or food increased, consumption (spending) would rise and this could push a household into debt.

Figure 6 Change in household financial flows, illustrative figures



Source: Vivid Economics based on Economics of Climate Adaptation Working Group (2009)

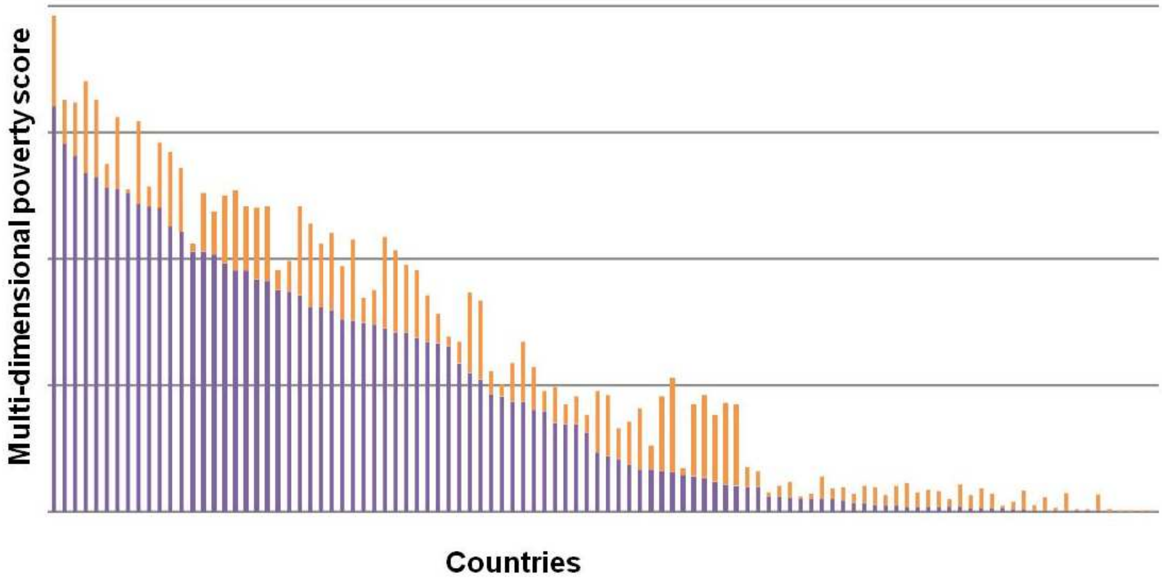
The impact on household income might be translated into the proportion of the population who fall below a poverty threshold. Such an indicator needs to be sensitive to changes in income distributions and changing concepts of poverty over time. Predictions of the proportion of the population below a threshold of income appear not to be available, and are likely to be uncertain. This is a challenge and further investigation would be needed to ascertain whether an income assessment is feasible.

4.4 Capabilities

For this outcome, a presentational method is adopted from the authors of the multi-dimensional poverty index, Alkire and Santos (2010). They show the proportion of households suffering multiple deprivations, aggregating by country and comparing between countries. An example is shown in figure 7.

Although it may not be possible to estimate the change in functionings of households from climate impacts at the present time, it appears that a combination of very low household income and quality of institutions and infrastructure together explain most of the variation currently. There are forecast to be very significant changes in multiple deprivations over time as low-income economies develop. While the use of capabilities offers a potentially useful and improved way of reporting impacts, further work is needed to examine the practicality of using such an approach.

Figure 7 Proportion of households with multiple deprivations in the future, with illustration of how the impacts of climate change could be shown



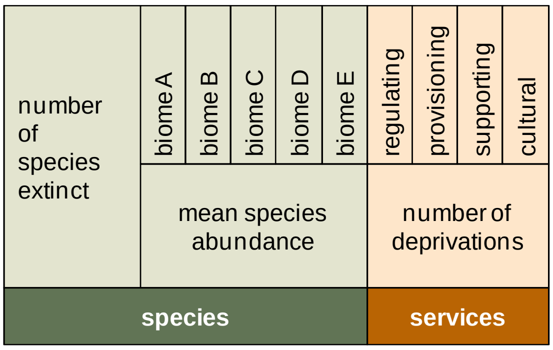
Source: Vivid Economics and Alkire & Santos, 2010

4.5 Biodiversity

Ecosystems provide two distinct sources of value. They provide the set of four services: provisioning, regulating, cultural and supporting; they also provide biodiversity (Millennium Ecosystem Assessment, 2005). Following this distinction, the suggestion is made that indicators be provided for biodiversity and also for ecosystem services. Ecosystem services indicators might follow the capabilities approach by focusing on potential deprivations in service. Biodiversity metrics capture local concerns through a species extinction indicator and wider concerns over loss of biodiversity through Mean Species Abundance.

Biodiversity indicators can communicate both the risk of extinction and the loss of mean species abundance due to climate change. It is desirable to provide both metrics because climate change has a particularly pronounced impact on the extinction risk of species endemic to biodiversity hotspots (Malcolm et al., 2005), while also having a more general impact on mean species abundance (Leadley et al., 2010). Risk of extinction captures the concern that climate change may destroy particular, emblematic or keystone species and degrade the biodiversity of specific localities. On the other hand MSA loss captures concern over a widespread, average loss in biodiversity.

Figure 8 A structure for reporting losses of species and ecosystem services



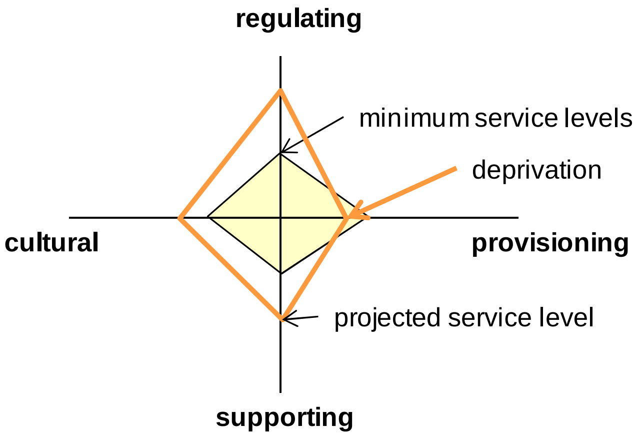
Source: Vivid Economics

MSA loss could be presented by the reduction in pristine area equivalent (following Alkemade et al., 2009).

The measurement of the flow of ecosystem services is a relatively young discipline, and, as section 5.4 describes, there have yet to be convincing estimates of the monetary value of non-market ecosystem services. This lack of data means that not even the current level of ecosystem service flow has been robustly quantified. This constrains any current presentation of ecosystem services to firstly judging the ordinal changes to baseline ecosystem services against a notional index of today's level of service. The degree to which climate change exacerbates the increase or decrease of service can then be qualitatively described.

No attempt has yet been made to quantify a minimum threshold for ecosystem services, but the concept and importance of such thresholds has been recognised (COPI, 2008). The concept of ecosystem service thresholds suggests an analogy with the capabilities framework used for human development, where minimal levels of service are defined and are used to identify deprivations that purely economic metrics fail to uncover. It may be difficult to make this assessment, but the suggestion made here is that further research into ecosystem services and minimum levels would be worthwhile.

Figure 9 The concept of ecosystem deprivations where limits to substitution are breached



Source: Vivid Economics

5 Summary of current estimates of the scale of impacts

Key Messages

Estimates of health impacts currently extend to 2030 and cover some major diseases. Health impacts are significantly diminished by development.

Biodiversity may be impacted by climate change as much as by all other human pressures combined. There are estimates of a significant proportion of remaining species abundance being lost.

Sea level rise and coastal flooding justify significant investment in protection to avoid placing significant populations and assets at risk.

Three of the most influential integrated assessment models produce similar central estimates of total damages, but differ in the composition of those estimates.

There is uncertainty in all areas of impact estimation.

5.1 Introduction

This section gathers evidence from the literature, where it is available, to populate the proposed indicators. All the data is from selected recent published sources. It is not a comprehensive survey. Much of the modelling work is fairly new and so some of the results have not yet been challenged and validated. Furthermore, some of the data is transformed here to make it amenable to presentation. The role of the data here is to illustrate the indicators proposed earlier.

The impacts presented here cover health, poverty, ecosystem services, biodiversity, coastal flooding and agriculture. To give an indication of their relative importance (and the variation in importance across the IAMs), the section ends with a comparison of the damage estimates from the FUND, DICE and PAGE models for similar scenarios, broken down by sector.

In this section, there is a focus on the presentation of context and relevant metrics, and the presentation of uncertainty is not a focus. Uncertainty is important and will be discussed in section 6. Ideally, all these aspects would be presented together, but it would require a quantity of resources that is beyond the scope of this project.

5.2 Health impacts

The impacts of climate change on health can be measured in deaths and in Disability Adjusted Life Years lost (DALYs lost). The measurement demands some complex attribution of climate impacts on the burden of disease, which was carried out for the Global Burden of Disease study (WHO, 2008).

The data presented here follows an established method of calculating the health impact of climate change (see Ebi, 2007). This method comes from McMichael et al. (2004), who calculated the impact of climate change on health for the WHO. McMichael et al. (2004) currently provide the authoritative assessment of global health impact estimates across climate change scenarios; however the Global Burden of Disease Study 2010, to be published in 2011, is expected to update the work of McMichael et al. (2004). Results presented here are comparable to the results of McMichael et al. (2004), although differences in regional results may occur due to varying regional definitions. Uniquely the impacts in 2030 are presented here and it is this presentation that necessitated calculation by Vivid Economics. Appendix 4.2 describes the method of calculation.

It is not possible to present impacts on life expectancy as recommended in section 4.2 because life tables for future periods are not available. Following the World Health Organisation approach, DALYs rather than QALYs are used, as DALYs are better suited to global analysis. Even though data availability restricts the development of the suggested indicators, figure 12 and figure 13 follow the suggested forms of presentation demonstrated in section 4.2 by figure 4 and figure 5.

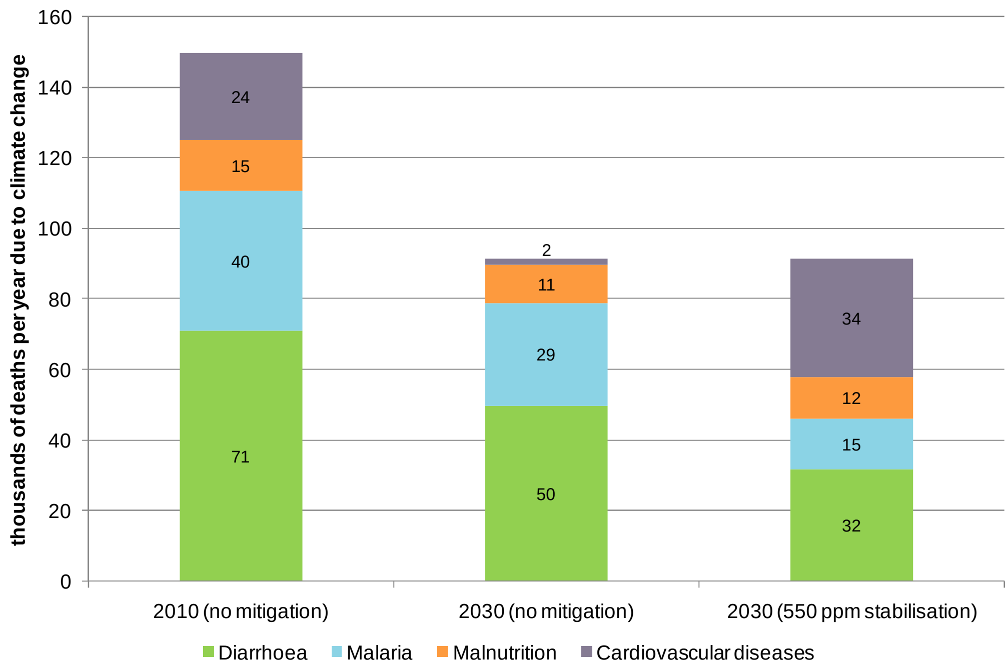
According to the Global Burden of Disease assessment, the global impact of climate change from additional mortality of cardiovascular disease, malnutrition, diarrhoea and malaria, due to climate change is currently 150,000 lives per year. The figures are lower in 2030, which is no surprise, since climate impacts are not expected to build up until later in the century and there is substantial economic development over nearly a quarter of a century.

Table 4 Total deaths due to climate change decline between 2008 and 2030 due to development

Region	Climate change (thousands)		All other causes (millions)	
	2008	2030	2008	2030
Africa	76	65	11.0	10.6
The Americas	3	0	6.3	8.4
Eastern Mediterranean	17	8	4.3	5.4
Europe	-1	0	9.7	9.5
South East Asia	48	16	14.8	17.1
Western Pacific	6	2	12.6	16.8

Source: Vivid Economics analysis (see appendix 4.2) and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004)

Figure 10 According to some estimates, climate change currently claims 150,000 lives a year; reducing to 90,000 lives per year by 2030, primarily due to economic development



Source: Vivid Economics Analysis and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004)

Under both a business as usual scenario and a 550 ppm stabilisation scenario, the health impacts of climate change in 2030 fall to 90,000 lives lost. The reduction in deaths from 150,000 to 90,000 is primarily the result of development. For example, McMichael et al. (2004) assume that when a country's GDP per capita reaches $6,000 then its population does not suffer an increase in malaria due to climate change; by 2030 many more countries may have such a level of GDP per capita than currently do.

Africa bears the brunt of climate change DALYs lost, both now and in 2030; this comes on top of a baseline rate of DALYs lost per thousand people which is twice the global average. In Africa, malaria and diarrhoea are already significant killers, and climate change compounds this problem. Both of these diseases claim large numbers of DALYs in other regions as well, with diarrhoea a major concern in South-East Asia, and malaria generating a high burden of disease due to climate change in other areas. Cardiovascular disease, malnutrition, diarrhoea and malaria are significant contributors to the general burden of disease, so changes in their incidence have a large effect.

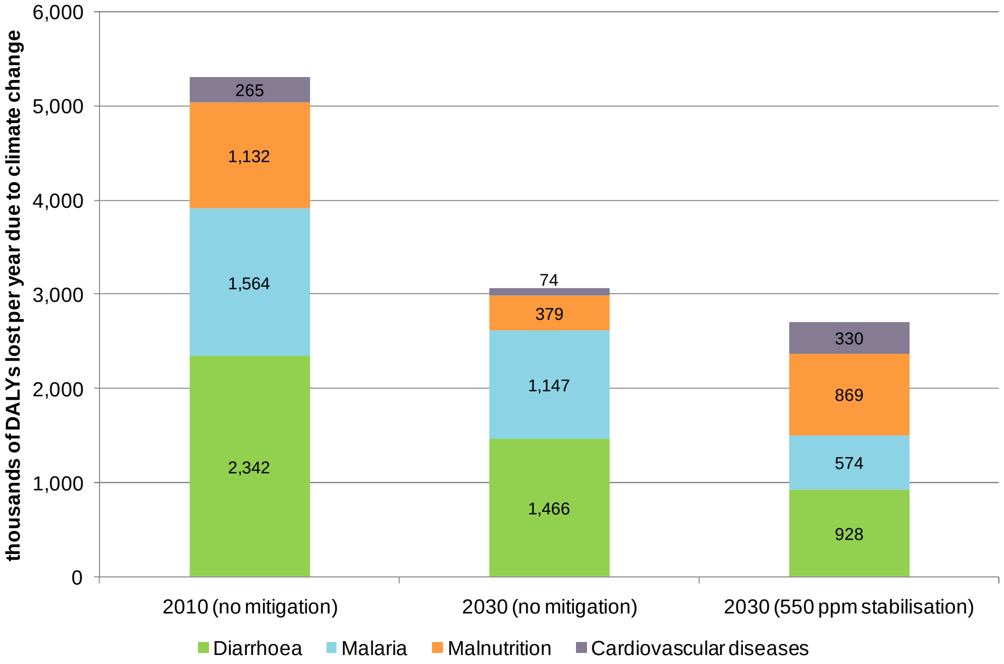
The health impacts of climate change assessed in the literature so far are small compared to other causes of disease, but the literature on health impacts is also incomplete. For example the time-scale considered by McMicheal et al. (2004), the results of which are presented here, is short, and so there is no exploration of health impacts at temperature increases of more than 1.3°C above the 1960–1990 average in 2030. In addition, the climate change impacts have been estimated taking into account only the average changes in climate, without consideration of extreme events and changing variability in the temperature.

Table 5 The burden of DALYs lost falls mostly in Africa, both now and in 2030

Region	Climate change (thousands)		All other causes (millions)	
	2008	2030	2008	2030
Africa	2,604	2,192	362	322
The Americas	51	17	142	154
Eastern Mediterranean	611	286	139	144
Europe	9	17	144	117
South East Asia	1,725	462	417	375
Western Pacific	304	91	255	250

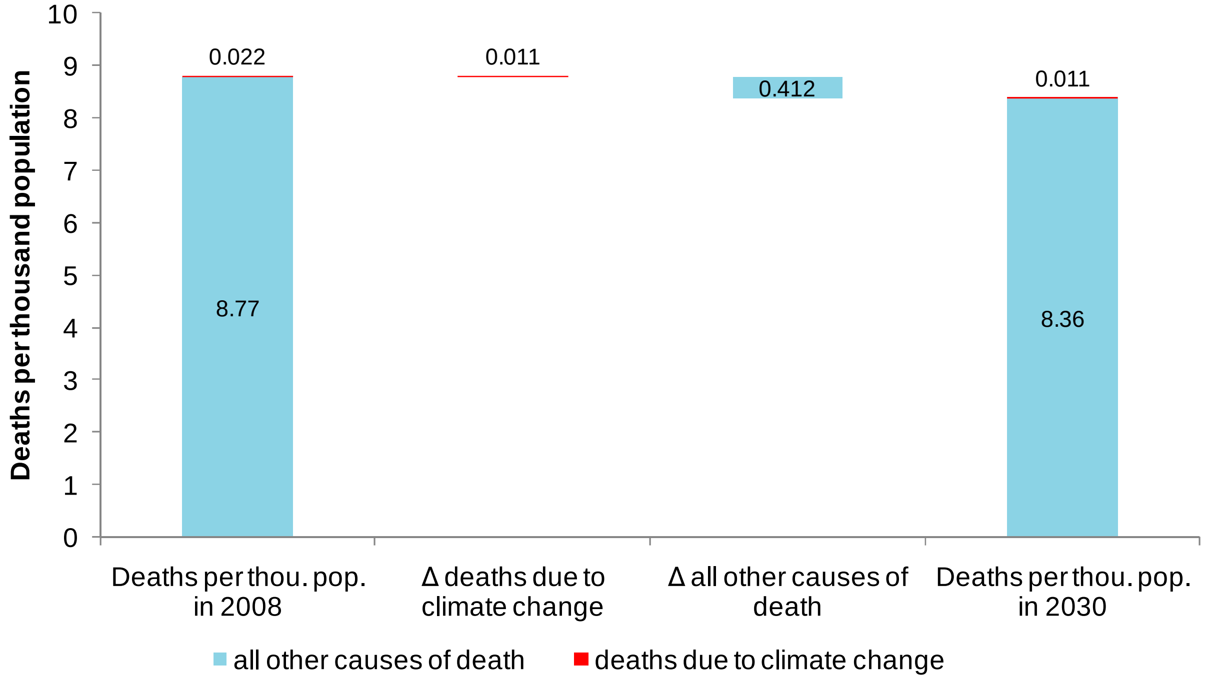
Source: Vivid Economics Analysis and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004)

Figure 11 Examination of DALYs lost rather than lives lost shows that mitigation reduces health impacts in the future



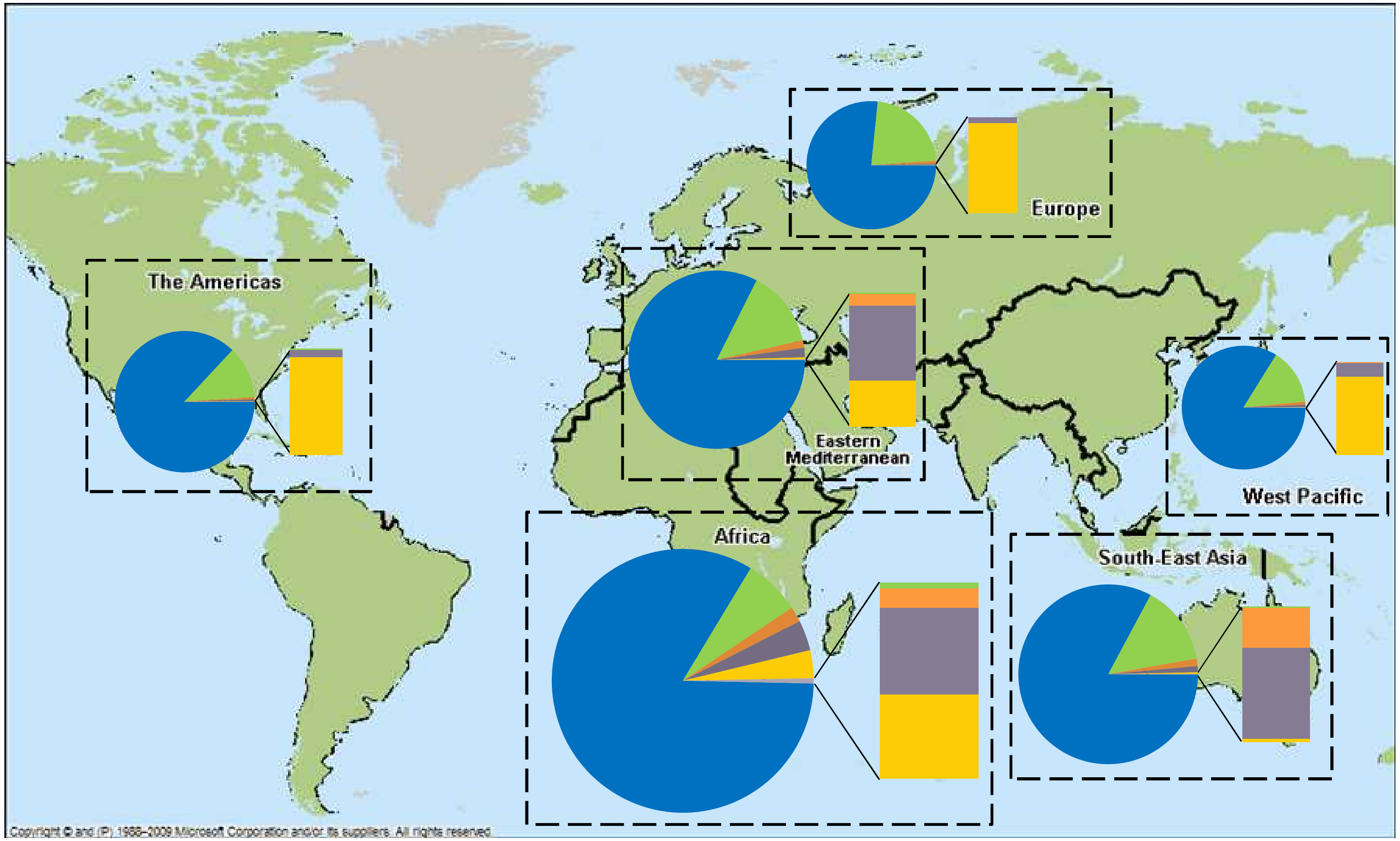
Source: Vivid Economics Analysis and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004)

Figure 12 The global impact of climate change on the crude death rate is small in comparison to the general burden of disease both now and in 2030, excluding extreme events, for which no estimates are available



Source: Vivid Economics Analysis and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004)

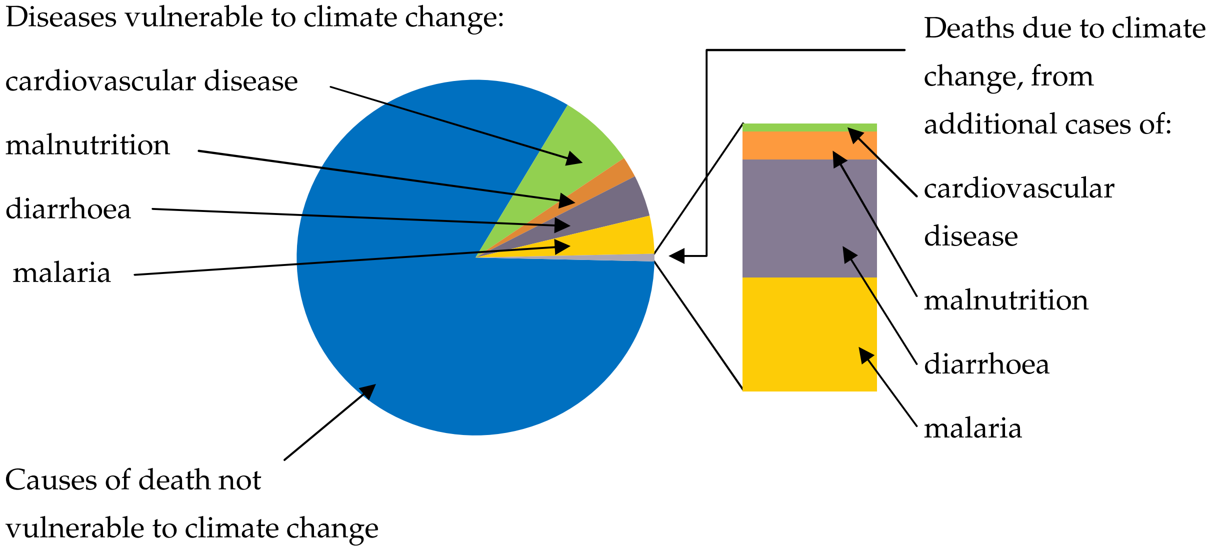
Figure 13 In 2030, of the impacts of climate change, malaria and diarrhoea claim the greatest proportion of DALYs and Africa bears the greatest burden



Source: Vivid Economics Analysis and WHO data (GBD, 2008, & Comparative Quantification of Health Risks Vol. 2, 2004

The size of each region's pie chart indicates the DALYs lost per thousand population relative to other regions; for instance, in 2030 Africa loses 244 DALYs per thousand population, while South-East Asia loses 132 DALYs per thousand population.

The pie charts show the proportion of DALYs lost per thousand population to the following diseases:



5.3 Poverty impacts

Poverty can be described by both income poverty, which could mean, for example, living on less than $2/day, and multi-dimensional poverty, which relates specifically to the capabilities of the poor.

There is currently no suitable data describing the impacts of climate change on poverty. This is due to the difficulty of attribution and because, for income poverty, the distribution of income levels in future society have not been estimated.

Work for the Stern Review provides some guidance. Anderson (2006) finds that sub-$2/day poverty persists in 2080 and is exacerbated by climate change. According to this source, the impact of climate change on Sub-Saharan Africa and South Asia in 2080 is, for a central case, to take an additional 22 million people below $2/day. With 95^{th} percentile climate change, 70 million more people face $2/day poverty. With 5^{th} percentile climate change 3 million more people suffer $2/day poverty due to climate change. Anderson assumes that income increases in line with the A2 scenario, and that the distribution of income within a region does not change.

An indicator of the impact of climate change on multi-dimensional poverty is also not feasible at present. The measurement of multi-dimensional poverty has improved recently due to the reporting framework of the Millennium Development Goals. However, the data and the understanding of causation are not yet good enough to forecast changes in multi-dimensional poverty due to climate change. Section 7.3 describes the research pathway that might be followed if one wished to employ this indicator.

5.4 Impact of climate change on ecosystem services

Climate change is expected to have a significant impact on the globe's biomes through increased temperatures and changed patterns of precipitation (Sukhdev et al., 2009). Part of the value of this impact is created through changes in services which these biomes provide. The valuation of ecosystem services in general, and non-market ecosystem services in particular, are explored in more detail in section 4.5.

It is not yet possible to populate an indicator for ecosystem services with complete data. Even major studies, such as the Millennium Ecosystem Assessment (2005) and The Economics of Ecosystems and Biodiversity (2009) have not established a detailed global picture of how ecosystem services will change due to the primary pressures on biomes, including economic growth. That said, such projects have laid a conceptual framework that describe how such a picture might be derived. In many cases, climate change is expected to act on biomes mainly through the exacerbation of existing pressures. In other cases, such as arctic ecosystems, it has a direct impact, for example, through the melting of summer sea ice. Research is progressing, some of which is within the Cost of Policy Inaction (2008) project, whose ambition is to fill a database of ecosystem service valuations and flows. So, within a reasonable time frame a rough picture of the impacts of climate change on ecosystem services may emerge. While it would have been ideal to present an indicator based on figure 9 in section 4.5, instead it is only possible to show a summary of the latest literature on the impacts of climate change on ecosystem services.

Table 6 Illustrations drawn from the literature on the impacts of climate change on ecosystem services contain examples of changes in ecosystemsthat are at present difficult to attribute to climate change and those where firmer attribution is possible

Biome	Ecosystem services	Examples of current changes which might be attributable, at least in part, to climate change	Projections	Ecosystem service impacts
Deserts and arid systems	Unspecified Desert Services Provides nutrients for land and oceans.	Evidence of expansion, at least in Sahel.	More extreme events likely, though disagreement exists.	Changes distribution of species. Increased precipitation may increase carbon sequestering.
			Increasing CO_2 leads to more biomass.	Helps the unspecified ecosystem services, but hurts nutrient provision for land and oceans.
			Increasing temperatures may increase evapotranspiration, leading to more desertification.	Decreases biomass, helps nutrient service, hurts unspecified service.
Grasslands and savannas	Hydrological services Provides resources Ecotourism Carbon storage	Studies show expansion into the Amazon due to declining rainfall, leading to fires and further 'savannaization'. Other studies show savannas being squeezed by increasing scrubland in southern and east Africa.	Non-linear and rapid changes likely, but difficult to predict.	
			Precipitation changes are the main driver. Changes in precipitation affect fire and disturbance regimes.	Decreased precipitation decreases all services. Each is identified as dependent on precipitation.
Mediterranean systems	Hydrological services Ecotourism Carbon Storage		Vulnerable to desertification and encroachment by neighbouring arid and semi-arid systems. May suffer strongest impacts from minor climate change. Effects from CO_2.	Hydrological services are sensitive and may be severely reduced. The ecosystem may switch from a carbon sink to carbon source by 2100 due to deterioration of water balance. Local species may not cope with changes, hurting ecotourism.
Forests and Woodlands	Provisioning (timber, fuel and other non-timber products) Hydrological Services Retention of Biodiversity Carbon Storage	Long-term studies are limited, but show, for example, uphill migrations of tree lines in Scandinavia and upward advance of alpine in Yunnan, China	IPCC AR4 predicts major changes with temperature changes over 3°C, mostly losses in boreal, mountain, and tropical regions but some expansion in climate-limited water-abundant forests. Climate change is projected to lead to northward expansion of boreal forests with a substantial time lag. Amazon rainforest is expected to dieback by 18–70%, though some argue the evidence is far from conclusive.	Moderate climate changes increase forest productivity through both warming and CO_2 fertilisation. Increasing drought, fire, and insect outbreaks with further warming reverses these benefits. Warming and CO_2 generally benefits the services, drying generally hurts the services.
Tundra and Arctic	Carbon Storage	Evidence suggests decreases in tundra area during the 20th century. Neighbouring tree lines and taiga vegetation encroachment has not been balanced by northward tundra movement.	IPCC AR4 rates these ecosystems as the most vulnerable.	May turn from carbon sinks to carbon sources. However, carbon storage may increase with polar deserts being replaced by tundra. Melting of permafrost is likely to increase methane emissions.
Mountains	Carbon Storage Hydrological Services	IPCC AR4 has highlighted above average warming in mountains that have led to water shortages and reduced glaciers, ecosystem degradation, due to	More of the same is expected – though there is an upper limit to upward tree line movement due to drying and higher evapotranspiration with warmer temperatures.	Climatic warming may release large amounts of carbon from the soils in montane systems and disrupt hydrological flows.

		land-use change and over-grazing. Also, upward movement of tree lines has been seen.		
Inland Waters	Provisioning of Water Provisioning of Food Carbon Storage		IPCC AR4 rates inland waters as highly vulnerable – particularly in Africa. Many lakes are expected to dry out. Arctic lakes are expected to have reduced ice cover duration and may have earlier and increased primary production.	Higher temperatures lead to water quality degradation and hurt lake productivity. Sea level rise will affect carbon storage and costal protection that coastal wetlands and peatlands provide.
Marine and costal	Provisioning (fisheries, building materials, biochemicals) Coastal Protection Carbon Storage Ecotourism	Sea level rise Ocean acidification	Ocean acidification and desalination, increased thermal stratification, reduced upwelling, increased wave height and storm surge, and sea level rise are all possible impacts.	Ocean acidification undermines coral reefs and costal protection, but increases brown algae biomass.
				Sea surface temperature rise degrades the survivability of certain species and generally decreases all ecosystem services and may trigger more extreme weather events.
				Sea Ice melting may affect provisioning
				Sea Level rise affects coastal erosion.

Source: Vivid Economics Analysis based on Campbell et al. (2009)

5.5 Biodiversity impacts

The impact of climate change on biodiversity is explored here through the loss in Mean Species Abundance (MSA) and the risk of species extinction as described earlier. Details on the modelling approach may be found in appendix 4.3. It might be worthwhile exploring alternatives to these two metrics.

An MSA index gives a score of 1 to a pristine biome, where there has been no human interference and original species are at their natural population levels. A score of 0 means that none of the original species remain in the biome. A 0.1 reduction in MSA is equivalent to, on the one hand, all species losing 10 per cent of their population, or, on the other hand, 10 per cent of species losing all their population. It can also be equivalent to a 10 per cent reduction in a biome's area.

The GLOBIO3 model (Alkemade et al., 2009) estimates regression coefficients describing biome loss in MSA due to temperature increases. It also estimates MSA loss due to human activity up to the year 2000. These data, aggregated across biomes to give regional impacts, are used here to explore MSA loss at different temperatures. Uncertainty relating to the estimates of regression coefficients is also explored.

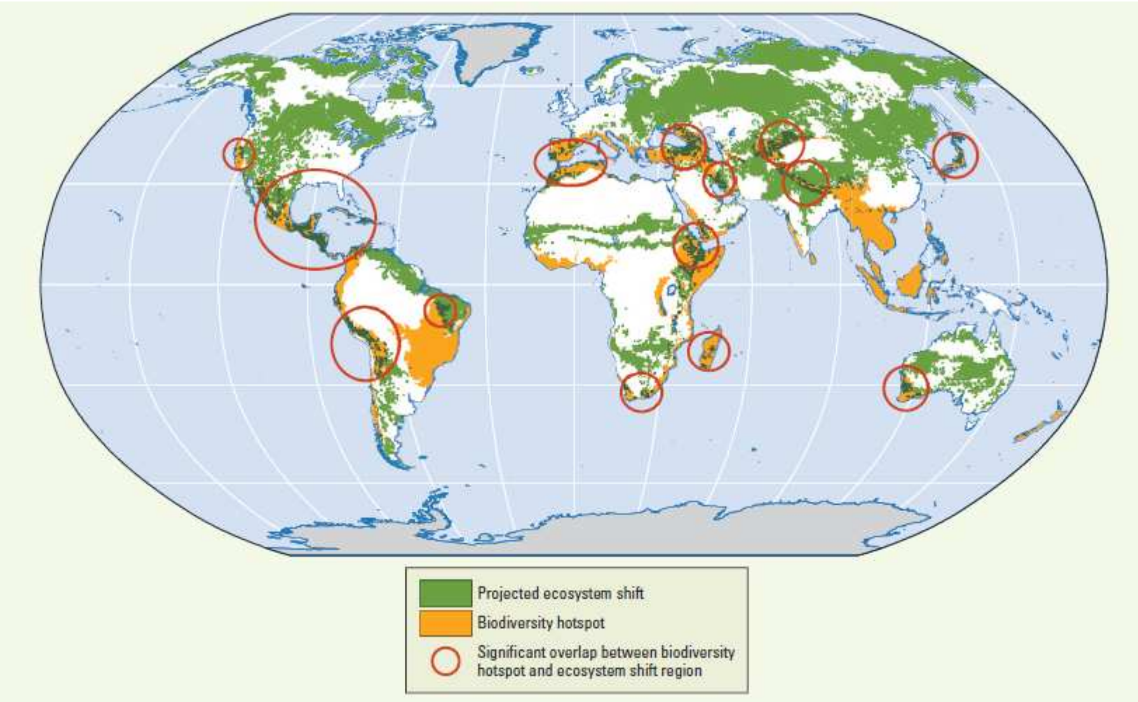
The analysis shows that even 2°C of warming above pre-industrial levels threatens the world with an MSA loss of 0.12, with some regions, such as Oceania, faring far worse, losing 0.18 MSA points. A loss of global MSA of 0.12 is equivalent to losing nearly 16 million km^2 of pristine environment, which is one and a half times the area of the United States.

If temperatures increase to 3°C then global MSA loss could, in a central case, increase to 0.18, the equivalent of the whole of Europe and the Former Soviet Union in its pristine state. However, at one standard error above of the central estimate, 3°C could result in a global MSA loss of 0.25. This is equivalent to the loss of biodiversity due to human activity up to the year 2000. Equivalent figures one standard error below the central estimates could also be examined. These estimates for 3°C have not been validated and are the product of extrapolation. The possibility of such a severe impact at high temperatures supports the suggestion that biodiversity is an important climate change impact.

The risk of extinction has yet to be robustly modelled on a global scale, so it is not possible to go further than the conclusion of the IPCC AR4 (2007). This conclusion was that 'approximately 20–30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5–2.5°C'.

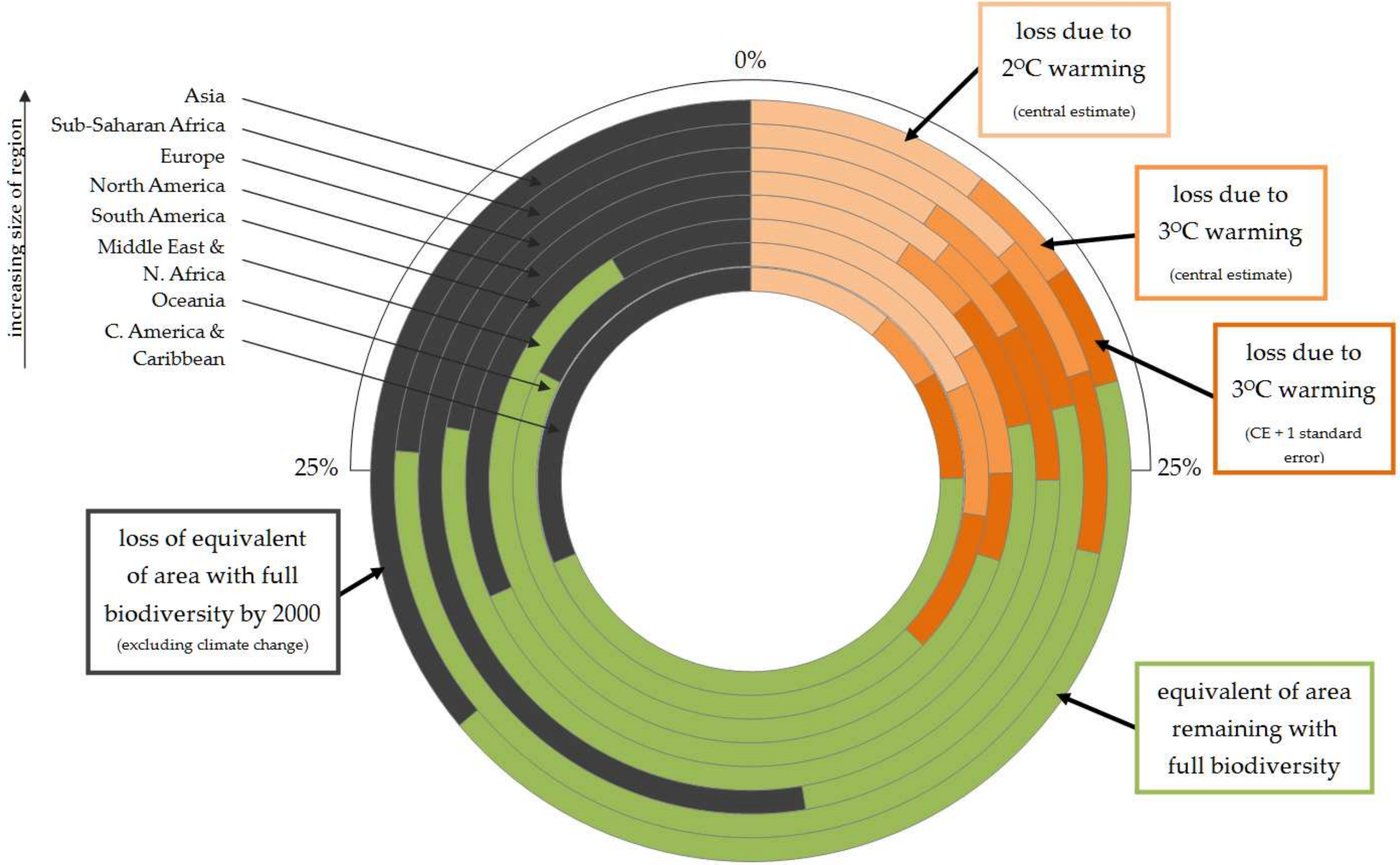
Attempts to assess the risk of local extinction are difficult to calibrate due to the variety of models used. In the World Development Report's presentation (World Bank, 2010), shown in figure 14, the impacts are shown as hotspots, where the greatest numbers of species are at risk of extinction, and as shifts of biome.

Figure 14 The World Development Report does not quantify the impact of climate change on biodiversity hotspots, opting to highlight the areas at risk



Source, World Development Report, 2010

Figure 15 Biome loss and degradation from human activity by 2000, and from projections of climate change. At 3°C of warming, there may be a risk of decreasing MSA by a level similar to human-induced losses so far



Source: Vivid Economics Analysis and GLOBIO3 data (Alkemade et al, 2009)

5.6 Impact of climate change on coastal flooding

Climate change will cause sea levels to rise, which could lead to coastal flooding (IPCC, 2007). The impacts might be felt by both the developing and the developed world.

Coastal flooding has two primary impacts: either people and assets (built and natural) are flooded, or costs are incurred defending people and assets against the rising sea. If sea defences are built then a smaller number of people may be flooded. For example the DIVA model estimates that 0.02 per cent of the flood plain population is flooded in 2055 if adaptation occurs. There has been no detailed exploration of partial defence in the literature.

The data presented in this section comes from the AVOID program, which uses the DIVA model, described in appendix 4.4. Coastal flooding impacts in 2055 are relatively insensitive to the mitigation scenario and therefore results for just three of the AVOID scenarios are presented: A1B (no mitigation), A1B.2016.R5.Low (A1B storyline with emissions peaking in 2016, a 5 per cent reduction in emissions per year till a low emissions concentration is reached) and A1B.2030.R5.Low (which is the same as A1B.2016.R5.Low with an emissions peak in 2030).

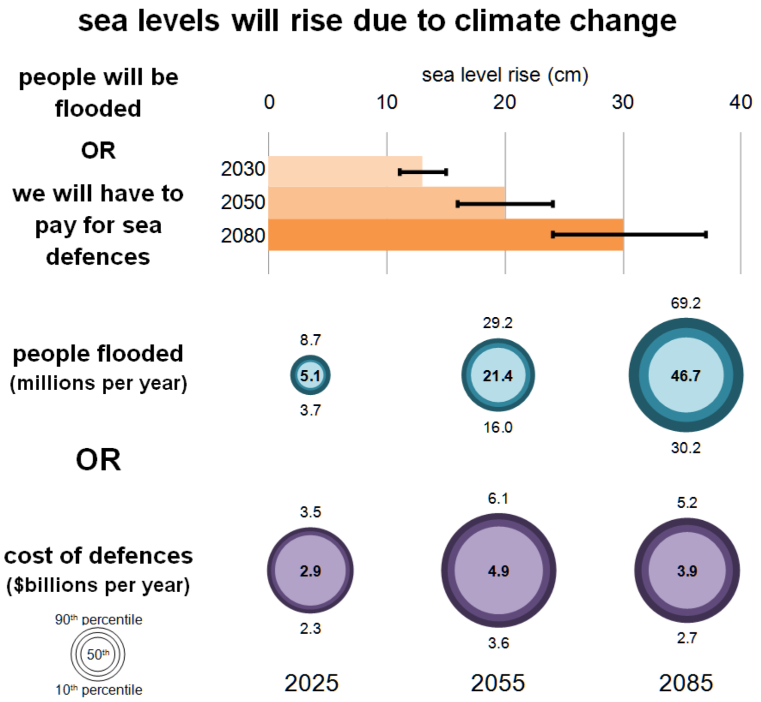
The central estimates from the A1B scenario are that climate change induced coastal flooding would affect 25 million people per year by 2055, but could be avoided with expenditure of $5.8 billion per year. By 2085 this rises to 74 million people flooded or $7.5 billion per year. Table 7 details the best and worst cases in 2055. The figures in this table do not show the impacts in the absence of climate change. Other flooding studies might have produced different estimates.

Table 7 Impacts of flooding due to climate change in terms of people flooded or the investment per year required to protect them, in 2055

	Best case	Worst case
A1B	18.4 million people flooded or $4.5 billion invested	33.9 million people flooded or $7.2 billion invested
2016.R5.Low	14.2 million people flooded or $2.4 billion invested	26.1 million people flooded or $4.7 billion invested

Source: AVOID (2010)

Figure 16 Choices will have to be made in the face of rising sea levels



Source: Vivid Economics Analysis and AVOID (2010) data

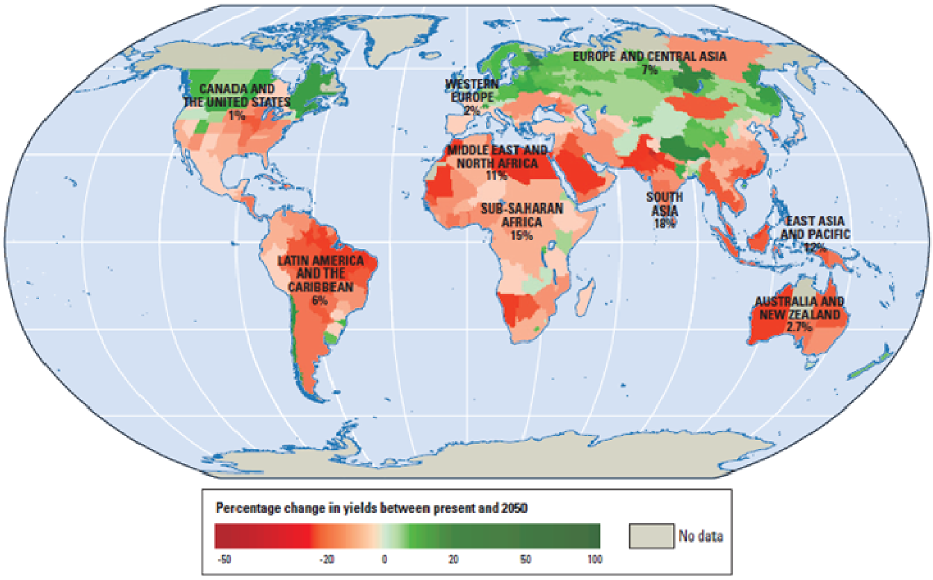
The defence versus people flooded tradeoff is presented in figure 16 for the A1B.2030.R5.Low scenario.

5.7 Agriculture

To show the scale of impacts on agriculture, the World Bank's analysis is reproduced. This is based on a survey of leading research. The World Bank combines changes in major crop yields, a biophysical indicator, with the share of agriculture in regional GDP, and thereby communicates the importance of agriculture to society. Changes in crop yields are denoted by colour coding, in figure 17, while the share of agriculture in GDP is denoted by a percentage, also in figure 17. It shows that climate change has some positive impacts for agriculture, mostly in regions where agriculture is a low proportion of income, whereas the most negative impacts are borne by the regions for which agriculture is more important. Only very limited adaptation, in the form of changes in crop planting dates, is accounted for, and major adaptation, such as changes in the area planted, crop varieties and types, and improvements in capital stock are not considered. This biases the estimates towards over-estimating negative impacts and under-estimating positive impacts.

There is a great deal of uncertainty over agricultural impacts. There are a number of global models predicting different levels of impact. One way to handle this would be to present a wide range of results, but the resources required to do that are outside the scope of this project. Here, no attempt is made to illustrate the degree of uncertainty, and central results from a single review paper are presented.

Figure 17 The severity of the impact of climate change on agriculture in developing countries is illustrated in this figure produced by the World Bank



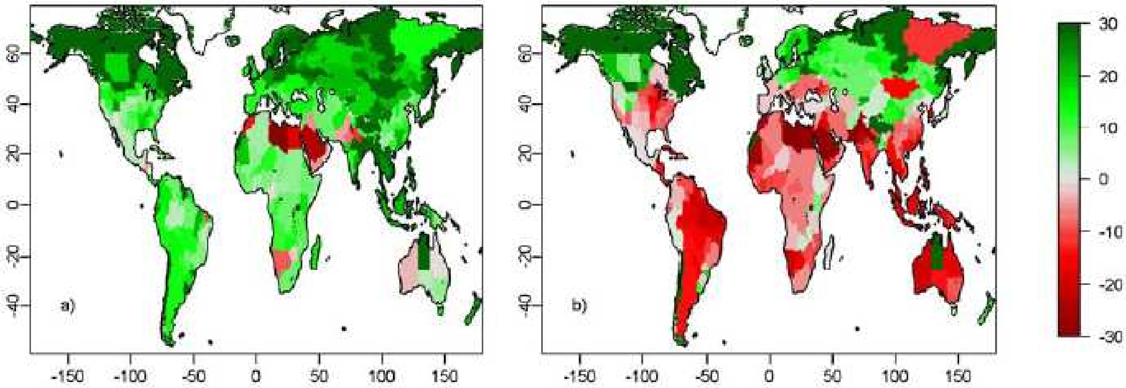
Sources: Müller and others 2009; World Bank 2008c.

Note: The coloring in the figure shows the projected percentage change in yields of 11 major crops (wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed) from 2046 to 2055, compared with 1996–2005. The yield-change values are the mean of three emission scenarios across five global climate models, assuming no CO_2 fertilization (a possible boost to plant growth and water-use efficiency from higher ambient CO_2 concentrations). The numbers indicate the share of GDP derived from agriculture in each region. (The share for Sub-Saharan Africa is 23 percent if South Africa is excluded.) Large negative yield impacts are projected in many areas that are highly dependent on agriculture.

Source: World Bank (2010)

Moreover, Figure 18's results assume no CO_2 fertilisation, although it could be a significant effect and is one of the key uncertainties in agricultural impacts (Muller et al., 2009). Figure 18 contrasts the impacts of climate change on agriculture when CO_2 fertilisation is assumed (left panel) and when it is not assumed (right panel) from the same underlying model that produced the data for figure 17.

Figure 18 Assumptions regarding CO_2 fertilisation can change the impact of climate change on agriculture from negative to positive



Source: Muller et al (2009)

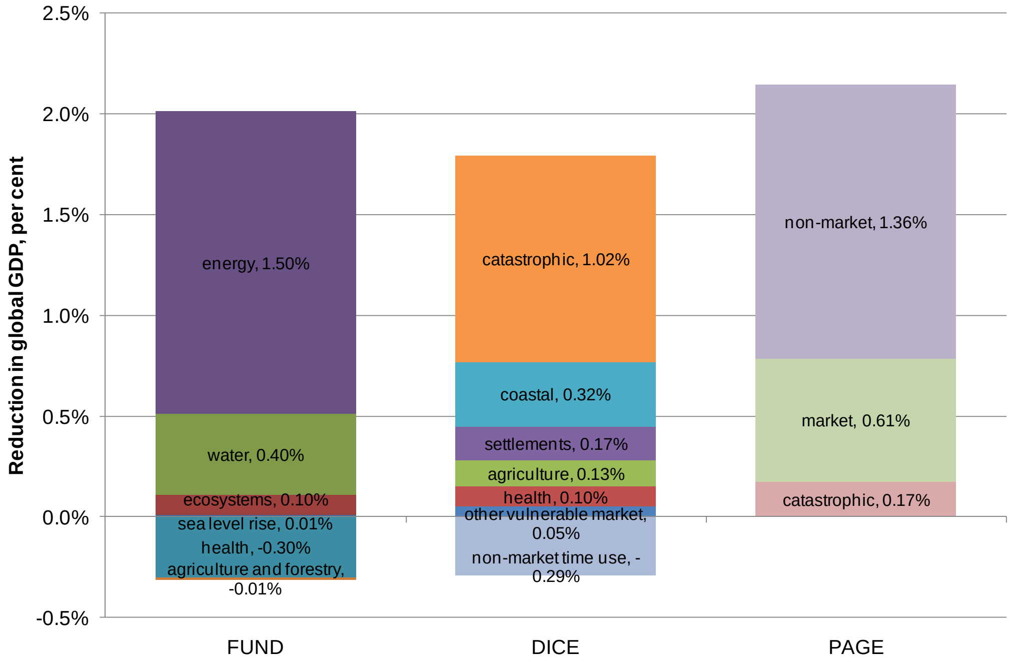
Notes: the figure shows the impact of mean climate change (averaged across 3 emission scenarios in 5 GCMs) on crop yields in 2050, expressed in percent change relative to 2000. The left panel shows the impact assuming high CO_2 fertilisation while the right panel shows the impact with no CO_2 fertilisation.

5.8 Sectoral climate change impacts estimated by IAMs

The global GDP impacts of the FUND, DICE and PAGE integrated assessment models, for 2.5°C of warming relative to 1990, are presented in figure 19. The figure shows that global damage is similar between the models, between 1.5 per cent and 2.1 per cent of GDP.

Integrated Assessment Models report impacts on several sectors, but the definition of sectors does not map neatly onto the sectors analysed in other research, nor in other IAMs. There is also significant variance in the impact estimates for individual sectors.

Figure 19 A comparison of the sectoral impacts of IAMs, for a scenario of 2.5°C of warming, reveals variance in estimates at sector level and similar overall impact estimates



Source: Vivid Economics Analysis and Warren et al. (2006) and Hope (2006) data

Notes: FUND and PAGE specify that 2.5℃ of warming relative to 1990 occurs by 2080. The FUND and the PAGE model use the SRES A2 scenario and DICE endogenously produces a scenario between SRES A2 and B2. Negative GDP impacts are gains and the chart shows gross impacts, i.e. the net impact for FUND is 2.01% - 0.31% = 1.7% damages and the net impact for DICE is 1.79% - 0.29% = 1.5% damages. The mean output value of net impact for PAGE is 2.14% damages. The 5th percentile output value of net impact for PAGE is 0.21% damages and the 95th percentile output value of net impact for PAGE is 6.56% damages. DICE and PAGE global estimates are aggregated from regions using output weights, which tend to give a lower damage estimate than population weights. The method of aggregation for FUND was not specified.

6 The handling of uncertainty in impact estimates and decisions

Key messages

Uncertainty in climate impacts estimates arising from futurity, complexity, linearity and ethical considerations.

The insurance sector is used to handling risk, and estimates the probabilities of events that may occur.

For climate impacts, probabilities of outcomes are often unknown. In this situation, expected cost-benefit analysis cannot be used in decision analysis.

Alternative decision rules are available. One, 'maximin', chooses the least worst option. Another, 'minimax regret', chooses the lowest regret option.

In these decision rules, the worst case plays an important role. The rules are cautious. The worst case is also evident as a motivation in recent key policy statements. For these reasons, worst case impacts estimation may be a priority.

6.1 Introduction

There is significant uncertainty about the impacts of climate change and it may not be possible to describe all uncertainties using a probability distribution. This raises particular challenges for decision-makers, whose standard economic appraisal tools rely upon probabilities.

This section tackles the question of uncertainty. It surveys the origins of uncertainty in climate impacts estimation, before considering its treatment in decision making, also making the analogy between climate policy and insurance.

6.2 The origins of uncertainty

There are many sources of uncertainty in the evaluation of climate change impacts, at every stage in the chain from the social, economic and technological forces generating emissions of greenhouse gases, through to the biophysical and socio-economic impacts of those emissions. There are also many different ways to classify the uncertainties.

There are arguably four main sources of uncertainty: (i) futurity; (ii) complexity; (iii) non-linearity; and (iv) ethical considerations.

Climate change is a long-term problem, by virtue of the long residence time of the principal greenhouse gas, carbon dioxide, in the atmosphere, as well as the other slow dynamic processes in the climate system and in the socio-economic impacts of changes in the climate system. Moreover, even socio-economic impacts of climate change occurring over the next few decades can cast a long shadow, through their impacts on investment and thus long-run growth prospects.

These long time-scales amplify climate-impacts uncertainties in an obvious way. One aspect, which becomes more uncertain the further into the future one looks, is the baseline socio-economic conditions. These determine emissions of greenhouse gases (relevant for the impacts of emissions today as well as in the future), as well as how well off and how numerous the population will be when the impacts of climate change occur, relevant for the estimation of human well-being.

The second source of uncertainty is complexity. The climate is a highly complex, open system, and depends in important ways on processes resolved at fine spatial scales, which are difficult to model. For this reason, Roe and Baker (2007) note the lack of progress on bounding the upper tail of the climate sensitivity despite the increasing body of research and observations. They show, using a stylized but representative model, that the climate sensitivity is highly sensitive to uncertainty in the net effect of complex feedbacks, such as the effect of clouds and water vapour.

The socio-economic system is also highly complex, and it has been argued that social scientists do not have analogous fundamental laws to rely on, even in relatively closed systems (for example, Beinhocker, 2007). Thus it follows that the socio-economic impacts could be more complex and more difficult to estimate. This complexity results in uncertainty about the adequacy of the models themselves.

The third source of uncertainty is non-linearity. Non-linearity is a common feature of environmental dose-response relationships, such as the damage function in economic IAMs mentioned above. The functional form of these relationships is uncertain in many cases.

Non-linearity and complexity interact as sources of uncertainty in climate impacts estimation, since the consequences of model mis-specification, due to the complexity of the system, are typically much greater when impacts are non-linear.

Finally, there is uncertainty about the social significance of climate change impacts, as embodied, for example, in ongoing debates about the parameters of the utility and social welfare functions, which come together in the social discount rate. While standard welfare economics takes for granted that human well-being can be measured in money units and aggregated, some scholars and commentators contest this claim. The authors of this report also note the continuing debate about how to make rational decisions in the face of deep uncertainty and ambiguity.

6.3 Climate policy as insurance

Recent research in climate change economics has begun to embrace uncertainty. One issue that has received particular attention is the existence of low-probability, high-consequence outcomes. Estimates of the impacts of climate catastrophes have long formed part of the integrated assessment modelling of William Nordhaus (DICE) and Chris Hope (PAGE) and appendix 5 details this work.

In a series of influential papers, Martin Weitzman (e.g. 2009) demonstrated the conditions under which decisions on mitigation can be driven almost entirely by the desire to reduce the likelihood and impacts of climate catastrophes, so that much debated issues in welfare economics, such as the appropriate rate of pure time preference, are less important.

The broader message of Weitzman's work is that catastrophes are important. He argues that most existing studies have not explored them sufficiently, and his recent work exposes Nordhaus' damage function in DICE to particular critique (Weitzman, 2010). He also states that, while willingness to pay to avoid a climate catastrophe is likely to be bounded, catastrophe avoidance is likely to be central to the case for mitigation and adaptation, and so climate policy is a form of insurance.

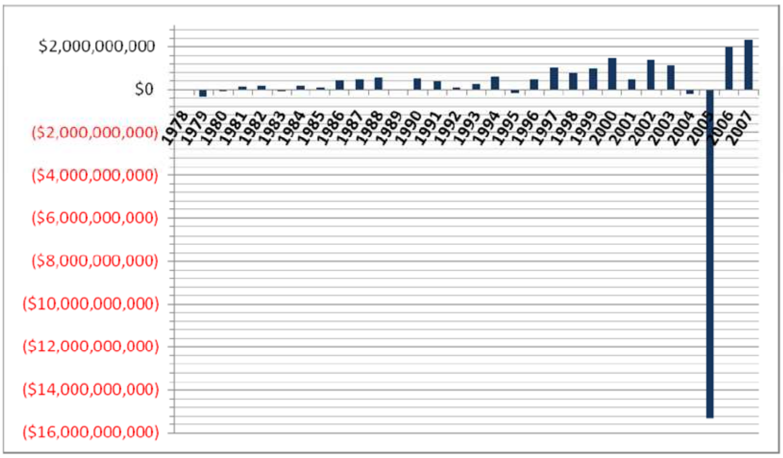
How good is this analogy between insurance and climate policy? A traditional insurance policy pays out a predetermined amount after an event. Here there is no pooling of risk, nor transfer to a third party. There is no post-event payout after a catastrophic climate outcome here. The policy is unlikely to survive to pay out, because catastrophic climate impacts pose a systemic risk for which there are no hedges. Instead, the pay-out of climate insurance is avoided climate damage. The greater the uncertainty of the magnitude of damages, and the stronger our aversion to uncertainty, the greater the value insurance will have.

Climate insurance works by ‘thinning’ the fat tail of low-probability, high-impact outcomes of climate change. Mitigation thins the tail by reducing the probabilities of high temperatures and associated impacts. Adaptation can also thin the tail by reducing some impacts. However, if the risk of catastrophic impacts cannot be avoided, then they may be less compelling as a reason for mitigation.

As insurers-of-last-resort, governments have a strong interest in managing the risks of catastrophe. Evidence suggests that the private sector is poor at insuring against systemic risks, with responsibility falling by default on government. An example of this failure was the underinsurance of damages from Hurricane Katrina. Thirty years of insurance premiums had not built up enough assets to meet the liabilities of the hurricane, as shown in figure 20.

Markets tend to fail to take appropriate action in the face of systemic risks. In the event of such market failure, damages are often transferred to the public realm. Thus government has a strong case for actively managing the risk of catastrophe, to correct the market failure of under insurance and to manage government's obligation to prevent harm to society.

Figure 20 The $15 billion in claims to the NFIP after Hurricane Katrina, shown against nearly 30 years of an otherwise unexceptional insurance program, illustrates the cost of ignoring low probability but high impact events



Source: Kousky & Cooke (2010) RFF issue brief 10-12

Note: National Flood Insurance Program premiums minus claims 1978–2007

6.4 The standard approach for known probabilities

The standard approach to economic appraisal of projects, and calculation of insurance premia, is expected value analysis. The expected value is the product of the value of the outcome and its probability. The framework assumes that the decision-maker is risk-neutral, which is usually appropriate, because risks can be diversified. In the case of public projects, it has been argued that the gains and losses of many small projects essentially cancel out.

Yet, if the project risk is systemic, so that it cannot be diversified away, the decision maker may be risk averse. A risk-averse decision maker places higher value on scenarios where the variance in possible outcomes is low. Such preferences can be expressed by a standard utility function. A detailed description is given in appendix 6.2.

If expected utility analysis is to be used, the variance in states of the world is described by well-defined probabilities, usually termed ‘risks’. It cannot be used where there are ambiguities or ignorance. These latter situations will be explored in the next sub-section.

6.5 Approaches where probabilities are unknown

We do not presently, and may not for some time, have good information about the probabilities of climate change impacts. Frank Knight (1921) famously drew a distinction between uncertainty, and risks, to which unique estimates of probability can be assigned. Keynes independently made the same point at around the same time. In contemporary economics, a situation in which the probabilities of the set of outcomes are not known uniquely is generally known as ‘ambiguity’.

In climate policy, the probabilities of impacts are not well-defined and so rather than expected utility analysis, other decision rules have to be used.

Other decision frameworks have been developed to account for ambiguity aversion. One such framework is the ‘smooth’ ambiguity model (Klibanoff et al. 2005), which is capable of representing a wide range of preferences over ambiguity, and is becoming increasingly popular (Millner et al., 2010, apply the model to climate-change mitigation). This model, like other ambiguity models, continues to assume significant levels of knowledge. For example, it works there are several conflicting models, each giving a different probability of catastrophe, and these models constitute the full set of possible models, and a probability can be assigned to each of its being the correct model. Unfortunately, it may be that these probabilities are unknown.

If the state of our knowledge is poorer still, so that there is insufficient information about probabilities to use these techniques, then it may be necessary to retreat to the use of very cautious decision rules. Maximin and minimax regret decision rules operate without reference to probabilities, instead they operate on a set of outcome values.

Maximin selects the option that offers the least-bad worst case, so that if the worst case occurs, at least it is not as bad as it could have been. This is equivalent to having an infinite level of risk aversion in a context where probabilities are known, which shows why it is not generally recommended for decisions under risk. The mitigation cost of such extreme caution may well be very high, as the choice with the best worst case may not be the choice with best other cases. Furthermore the probability of the worst case occurring may be very small.

Minimax regret selects the option that minimises the maximum regret. Regret is the difference between the best case and the worst case. If regret is minimised then the best opportunity our choices present is not ignored. In contrast to maximin, minimax regret is less cautious, because it trades off the severity of the worst case with the benefit of the best case. However, minimax regret still ignores the value of intermediate cases and the probabilities of the best and worst cases occurring.

These decision rules apply caution in situations where probability information is lacking altogether. Decision rules under ambiguity are a work in progress in decision theory. As yet, there is no consensus on their application.

6.6 A choice of approach

If one can characterise the level of uncertainty and the preferences over caution then an appropriate decision rule can be chosen.

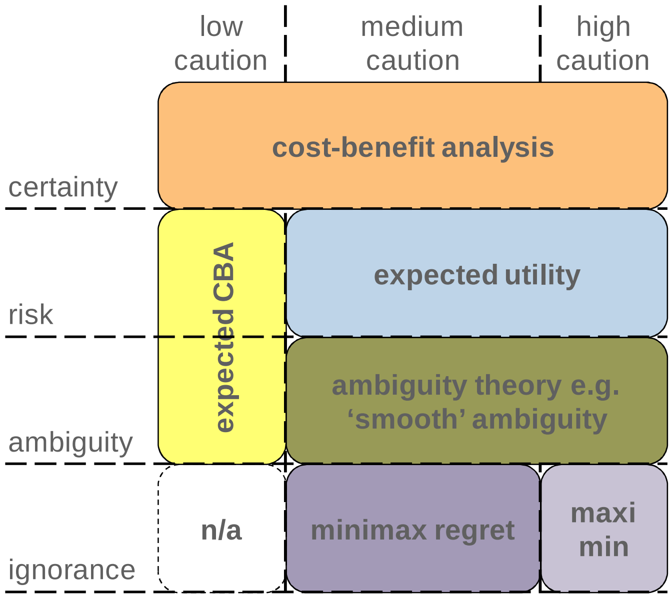
In a certain world, a traditional cost benefit analysis can be used. In the presence of risk but not risk aversion (because there is no systematic risk), the cost benefit analysis can be performed on a project's expected value (i.e. expected CBA).

If the decision maker is risk averse and probabilities are well-defined, then decisions can be made on the basis of expected utility, but if the probabilities are ambiguous then a preference over ambiguity may be required.

If there is no knowledge of the probabilities of outcomes (but the best and worst cases are known), it is possible to dispense with them altogether and focus instead on minimising the maximum regret that might occur. A highly cautious decision maker might also dispense with information on the best cases and focus only on the worst cases, adopting the maximin rule.

This set of rules and circumstances is summarized in figure 21.

Figure 21 Decision rules for different states of knowledge of probabilities and degrees of caution



Source: Vivid Economics

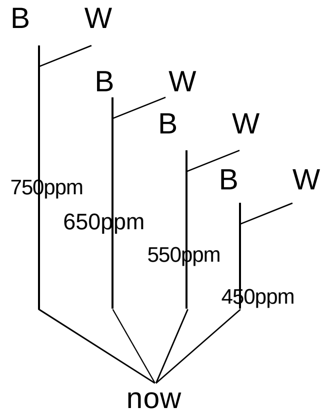
It is becoming apparent that uncertainty in climate change is too valuable to ignore but there is little consensus on how to handle it. A way forward is thus not immediately apparent, although the matrix makes tentative steps toward providing a practical solution for policy makers. If the policy issues of uncertainty are to be resolved, there are three tasks:

- determine, given our knowledge, the extent to which uncertainty is the key motivation for action on climate change;
- appraise the extent to which our knowledge falls short of the standard required for robust decision rules;
- evaluate acceptable levels of caution and acquire knowledge to reduce the level of caution.

6.6.1 *Practical difficulties with decision rules*

In applying decision rules to uncertain impacts, the options and their outcomes can be organised into a tree and a corresponding table. The example below focuses on the best and worst outcomes, in preparation for estimation of the minimax regret and maximin strategies, although it can be generalised to any of the approaches above in figure 22.

Figure 22 The expenditure and damages associated with the range of outcomes for each option is estimated, the best and worst outcomes recorded and the regret value is calculated by subtracting the best overall outcome from the worst outcome in each state



	If best occurs	If worst occurs	Max regret
No action (750ppm)			
Stop at 450ppm			
Stop at 550ppm			

Source: Vivid Economics. Note: this is an illustration of how the table and event tree are each laid out.

Most decision rules are designed to work with fully commensurable outcomes measured on the same numéraire, such as money. However, climate impacts are not fully monetised. This makes for a more complex presentation, in which weights would have to be applied to the individual impacts, which is effectively what monetisation does. The table would take a form such as that illustrated in table 8, once weights had been applied to the impact categories.

There are advantages and disadvantages to processes of explicit weighting such as this, which are familiar in the field of decision analysis (sometimes known as multi-criteria analysis). In particular, the elicitation of weights is inherently subjective, which some regard as increasing legitimacy, while others regard it as decreasing legitimacy.

Table 8 A regret table which preserves the detail of incommensurable impacts

Indicator	Regret from 450ppm	Regret from 550ppm	Regret from 650ppm	Regret from 750ppm
GDP loss from damages and expenditure				
DALYs lost				
Species lost or threatened				
Increase in households in poverty				
Cultural assets lost				

Source: Vivid Economics

Note: the table is intentionally blank.

6.7 Recommendations on uncertainty

In section 6.6 there is a framework to guide the choice of decision strategy given levels of precaution and knowledge. Here is a summary of the likely consequences of applying these decision strategies and discuss the value of information in relation to these choices.

In general, it is clear that where impacts are uncertain, estimates across the full range of scenarios might be recorded. Furthermore, in order to construct outcomes, sectoral estimates may be collated and based on a common set of scenarios. This may require a degree of coordination across impact studies.

The maximin strategy chooses an emissions path which minimises the worst case outcome. In practice, some of these worst case outcomes may persist with even the lowest emissions projections, because the science may be unable to refute the possibility of the outcome occurring. One might introduce an arbitrary cut-off at a low level of probability, which is the approach taken by the UK Climate Change Committee. Then outcomes below the probability threshold would be excluded. This expresses the maximin strategy as the virtual elimination of aggregate highly negative outcomes, whatever the cost. This is a cautious approach and it maps closely onto the CCC’s decision rule.

The minimax regret strategy chooses an emissions path which minimises the difference between the best and worst outcomes. It potentially results in a higher emissions path than maximin, because the regret strategy takes into account the possibility that impacts could be low. Thus the minimax regret strategy is less cautious than the maximin. The better the best outcomes, the more different become the minimax regret and maximin strategies. If the costs of action are significant relative to the impacts, then the minimax regret strategy can involve higher emissions than the maximin strategy.

The effect of the minimax regret strategy might be to reduce emissions to the point at which catastrophic impacts are no longer a possibility, provided that the costs of mitigation is less than the damage from the catastrophic impact itself. This is a cautious strategy and might lead to similar policy recommendations to the minimax result. That is, unless the cost of mitigation is sizeable relative to the cost of catastrophic impacts. Thus it may not matter much which of these two strategies is adopted.

Some of the major sectoral impacts cannot be monetised, which means that no overall single indicator of impact can be constructed when ranking poor outcomes to find the worst and best. Nevertheless, the decision maker can compare emissions paths which eliminate some or all of these poor outcomes, and can compare them against the costs of reducing emissions consistent with those emissions paths. The decision maker could go further and apply weights to the impacts.

The cost of uncertainty, and the value of research to reduce the uncertainty, is the difference in mitigation cost incurred under these strategies and a strategy closer to the expected utility strategy. Since the expected utility strategy is not known, the value of the research cannot be estimated *ex ante*.

7 Priorities for improving the evidence base

Key messages

There are suggestions to be made which might improve climate impacts reporting, but not all of these will turn out to be feasible.

Some are in fields of research which are highly specialised. The next step might be to elicit comments from experts.

Across all sectors, more knowledge of the impacts of extreme weather and of climate tipping extremes is desirable.

In health, DALYs and life expectancy are promising metrics. Suggested priorities are to extend estimates to cover weather extremes, a wider range of diseases and time beyond 2030.

In poverty, the multi-dimensional poverty index might be an aspirational metric. Suggested priorities are: test its feasibility, prepare future estimates of income and income distribution, establish the drivers of the index and begin to apply results from sectoral studies.

In biodiversity, mean species abundance, extinctions and ecosystems services are possible metrics. Suggested priorities are: devise a suite of metrics that sufficiently describes biodiversity impacts, further develop the modelling of mean species abundance, progress research into the effect of migration on extinctions, and begin to build a set of baselines for ecosystem services.

In agriculture, money may be used as the metric. Priorities may include the validation of aggregations of crop models, further exploration of the role of adaptation, and work to reduce uncertainty in the effects of carbon dioxide fertilisation.

7.1 Introduction

The paper so far has explored current metrics and has offered improved indicators. Real data has been used to illustrate them. This exercise has exposed some of the limits of current knowledge. However, this study has lacked the resources to interview sector experts and so the conclusions on the state of knowledge and timescales for completing impact assessments are highly tentative.

This section suggests the research that could establish a set of relevant and informative indicators in the health, poverty, ecosystems, agriculture, energy, extreme events and flooding sectors. A tentative opinion on the feasibility and timescale of completing the required research is also offered. These tentative conclusions might now be placed before experts who are better placed than the authors of this report to judge what is realistic given the current state of their fields of work.

7.2 Health indicators

Two of the three recommended indicators, DALYs lost and deaths per thousand population can already be created to 2030, as section 5.2 demonstrates. The third indicator, change in life expectancy, which was proposed in section 4.2, requires forecasts of life tables which were not available.

In general, health impacts work so far has not considered changes in the variability of climate. Health impacts of extreme periods of high temperature, high or low precipitation and other weather-related disasters could also be considered. Weather-related disasters can be accompanied by severe health impacts, such as water-borne disease and depression, and climate change might exacerbate the frequency and intensity of these weather extremes. To date, health impacts from these weather extremes have not been comprehensively estimated. Given that this could be responsible for a significant proportion of health impacts, research in this area might be a priority. Current climate models could provide at least indicative estimates of heat waves, droughts and flood events, so work could progress quite quickly, with broad estimates of impact delivered within 3 years.

The health response to climate change is currently being updated, via the Global Burden of Disease Study 2010 update. This study vehicle could be used to extend the assessment to 2050.

7.3 Poverty indicators

Two poverty indicators are recommended, an indicator of income poverty and an indicator of multi-dimensional poverty.

The impact of climate change on poverty requires estimates of the market impacts of climate change. This is currently estimated using IAMs but can also be estimated by aggregating the sector indicators of health treatment needs, agricultural output, energy costs, adaptation costs to flooding and the loss of assets due to extreme events.

Future income and income distributions would be needed as well as a choice of poverty threshold level in the future. Future incomes can and are estimated but, so far, future income distributions have not been.

There are significant challenges to estimating impacts on a multi-dimensional poverty indicator. These challenges relate to fundamental understanding of the causes of poverty as well as the impacts of climate change on those causes. Some of the dimensions of poverty, such as living standards and education, are related not only to income levels and health status, but also to damage from extreme events. For this, both extreme events due to climate change and their impact on assets and access to services would have to be well-characterised. It might take some time, perhaps 10 years or more, before a robust multi-dimensional assessment of climate impacts could be completed.

7.4 Ecosystems

Ecosystem indicators divide into ecosystem services and biodiversity indicators, reflecting the instrumental value of ecosystem services and the intrinsic value of biodiversity.

7.4.1 Ecosystem services

An indicator of ecosystem services combines the impact of climate change on the flows of service from an ecosystem and the value of these services. The measurement and valuation of services may be at present a source of greater uncertainty than the natural science of ecosystem change, which is itself imperfectly understood.

The measurement and valuation of ecosystem services benefits is an ongoing research effort (for example, see COPI, 2009), but the state of current knowledge is not good enough to provide a quantitative indicator of even baseline ecosystem services in some ecosystems. Any indicator of the impact of climate change on ecosystem services necessarily lags the development of such core knowledge.

It is widely accepted that ecosystem services are in general declining at some cost to society; and it is expected that climate change will exacerbate this trend. Therefore, as far as ecosystem services are a concern, they are a research priority, as the impact of climate change is likely to be significant. It might be 10 years or more before robust estimates of climate change impacts on ecosystems services are available for all major ecosystems.

7.4.2 Biodiversity

Two indicators are required for biodiversity. These are a broad measure of biodiversity loss, provided by, for example, Mean Species Abundance (MSA) loss, and a local measure of loss in biodiversity hotspots, provided by a metric of species at risk of extinction.

MSA loss describes the average loss of biodiversity across a region. It speaks to the existence value that is placed on biodiversity in general. However, there are also dimensions of diversity, such as evenness, which MSA might not capture. As stated earlier, there may be alternative measures that would perform as well or better as indicators of impact. This might be a matter for discussion among experts in this field.

MSA loss currently has a global modelling framework in the GLOBIO3 model which might be adequate for broad estimates of MSA loss. However, there is still considerable uncertainty. GLOBIO3 relies on just two underlying models to define the impact of climate change on ecosystems, the IMAGE and EUROMOVE models. Furthermore, the response of MSA loss to temperature is linear, which neglects the commonly held view that impacts increase at higher rates of temperature change.

Species at risk of extinction focuses on the loss of species at a local level, indicating the concern for particular totemic species or special areas of high biodiversity. Current estimates of species at risk of extinction utilise climate envelope modelling, where a species' survival is defined by the size of its 'envelope' of suitable habitat. The characterisation of a species' climate envelope is a difficult and uncertain science. Furthermore, migration requires dynamic envelopes be modelled. Ecosystem dynamics are hard to model, especially given the number of highly heterogeneous species involved. For example, it may be that it proves difficult to reduce uncertainty due to migration.

The next step is to explore the options for progressing biodiversity impacts assessment with the community of experts already working in this field and to assess feasible timescales for the elicitation of a comprehensive impacts assessment.

7.5 Agriculture, energy and extreme weather indicators

7.5.1 Agriculture indicators

Two indicators are recommended for agriculture. The change in yield and the change in the monetised value of output.

Regardless of the indicator used, there are a number of uncertainties in the estimation of agricultural impacts. Among these are the effect of CO_2 fertilisation and the extent of adaptation. If the greater levels of CO_2 fertilisation affect that can be made to occur in laboratories were to occur in the natural environment, then agricultural yield might increase for some crop types in the majority of regions. However limiting factors, such as water availability and the response of crops to heat stress, particularly at 3°C temperature rise, are likely counter these effects. If no CO_2 fertilisation is assumed then climate change can significantly reduce yields in most regions. The extent of CO_2 fertilisation is still contested. Given the importance of agriculture to the world economy and the sensitivity of agricultural impacts to CO_2 fertilisation, this is a high priority research area. Adaptation is also a key sensitivity, for example, if farmers can change their crop types to suit the new climate then impacts may be significantly reduced. The degree of adaptation that is modelled or assumed is not consistent across model types. A modelling framework that treats adaptation consistently would help to clarify this uncertainty.

There are many other, currently unquantified, aspects, such as extremes of weather, pests and diseases, so there is much work to be done to elucidate the full impacts of climate change on agriculture.

The change in yield is provided by crop models or, more recently, Dynamic General Vegetation Models (DGVMs). Research is required to validate aggregations of crop models or DGVMs as the global assessment of the impact on agriculture is in its early stages. The change in output is estimated by Ricardian models or by running changes in yield through agricultural trade models.

Again, this is a large field, and one where specific expertise is needed to comment in detail on the next steps required and feasible timescales for completing them. There is a large body of work already published and a number of global models are used. However, there are still substantial controversies and omissions. This suggests that a timescale of 5 to 10 years for resolving the main issues might be feasible.

7.5.2 Energy indicators

The key energy indicator is the change in energy expenditure, in total and at a household level.

The estimation of changes in heating and cooling degree days is fairly robust. The difficulties in forming an energy indicator lie in converting degree days into energy use and transforming energy use into energy costs. A view on energy use requires an understanding of the efficiency of future heating and cooling technology. Monetising this energy use requires estimates of future energy prices. Both technology forecasting and energy price forecasting involve significant uncertainty. Despite this, estimates of energy cost that have been attempted, for example in the FUND model, and suggest that the energy cost impact of climate change may be significant. Research to quantify the worst and best case energy costs may be a good response to the potentially large but uncertain impact of energy use due to climate change.

7.5.3 Extreme weather indicators

Extreme weather events, as well as contributing to other indicators, such as health and poverty, could destroy economic assets in their own right. The cost of extreme events can be very large, as Hurricane Katrina and the 2010 floods in Pakistan demonstrate. However, it is an evolving area. When climate models can provide sufficient information on the likely changes in intensity, location and frequency of extreme events, which is a significant research task, then insurance industry techniques, as detailed in appendix 2, can be applied to estimate the assets lost. Expanding the coverage of asset at risk information may not prove difficult, as frameworks for such data collection exist in the insurance industry. Again, this is a highly specialised area, to which experts would be better able to speak to feasibility and timescales than the authors of this report. Nevertheless, it is clear that the current generation of global climate models are able to make some contribution to this field, but that it will be at least the next generation of climate models, if not the one after that, which is able to provide a comprehensive characterisation extreme events. This suggests that the timescale is more than 5 and nearer 10 years.

7.6 Flooding indicators

7.6.1 Coastal flooding

Indicators of the impact of coastal flooding concern the cost of protection and the number of people flooded.

The cost of protection is currently estimated using the DIVA model. On the one hand, the model is relatively robust, with the changes in storm surge due to climate change an uncertainty yet to be resolved. This may be difficult to resolve as it requires an understanding how winds to change due to climate change. On the other hand, it assumes perfect foresight and instantaneous response, and ignores loss of natural assets.

The number of people flooded depends on protection against sea-level rise. This indicator is currently estimated using the DIVA model. It could be improved with accurate headcounts of coastal population and forecasts of how coastal population will change over time. This is likely to be a relatively easy research task. It might perhaps be completed within three years.

7.6.2 Fluvial flooding

Fluvial flooding might be hard to defend against. More needs to be known about the cost of assets damaged, the number of people flooded and the costs of defence. The estimation of fluvial flooding impacts is subject to uncertainty and significant modelling challenges.

Estimates of fluvial flooding impact require the integration of precipitation and geographical information. Neither of these sets of information is currently available, at a great enough degree of resolution, for a wide set of regions, to allow meaningful global modelling of impacts. However local examples, such as the UK foresight program (Foresight, 2004), do exist. Improving the resolution of precipitation data is likely to be feasible within a generation of GCMs, but even then, the resolution may still not be sufficient for fluvial flood modelling.

If the mechanics of fluvial flooding due to climate change can be well-characterised, then understanding the assets and people at risk is relatively easy. Similar data collection steps to those required by the extreme weather event and coastal flooding sectors would need to be followed.

There are likely to be continuous improvements, and within 5 years, these are likely to be significant, but comprehensive fluvial flooding estimates might be closer to 10 years away.

7.7 Research priorities

We have identified health, poverty and ecosystem indicators as key indicators due to their importance in human well-being. Their prominence makes them a research priority.

Health impacts may be a top priority because of the maturity of the research program. Poverty indicators will have a significant audience and it is feasible to estimate income poverty impacts within a reasonable time scale.

Ecosystems may not resonate with as broad a constituency as health and poverty and the research program is long and arduous. However, ecosystem impacts are likely to be considerable and ecosystems in general are in decline, which is likely to have a significant cost to society. Therefore research on the value of ecosystems is very worthwhile.

Extreme weather events and agriculture are two other sectors worthy of research as they influence health and poverty outcomes and because they are have a wide audience on their own merits. The research needs are on climate science, CO_2 fertilisation and agricultural adaptation. Agricultural research is likely to yield results sooner than extreme weather events research given the type of work necessary and the literature that already exists.

7.8 Summary of indicators and research requirements

A set of summary tables of recommended indicators, their type of valuation, aggregation and their climate science and impacts research needs are provided in this section. The tables correspond to the discussion in sections 7.2 to 7.6, where the current state of affairs is outlined.

Table 9 Indicators for health impacts of climate change which could be estimated in a short timescale

<table>
<tr><th colspan="2">Suggested indicators</th><th colspan="6">Research needs of suggested indicators</th></tr>
<tr><th rowspan="2">Indicator</th><th rowspan="2">Valuation, monetisation and aggregation</th><th colspan="3">Climate science</th><th colspan="3">Socio-economic research</th></tr>
<tr><th>Requirement</th><th>Feasibility</th><th>Time scale</th><th>Requirement</th><th>Feasibility</th><th>Time scale</th></tr>
<tr><td>Disability Adjusted Life Years (DALYs) lost</td><td>DALYs value health states relative to each other. Monetisation is feasible but can result in different values being placed on populations with different income levels. Aggregation can occur at a country level.</td><td rowspan="3">Extreme periods of prolonged high temperatures, and of low or high rainfall.</td><td rowspan="3">Current climate models could be used to estimate heat waves, droughts and flood events.</td><td rowspan="3">1 to 3 years.</td><td rowspan="3">Impacts (risk factors) above 3°C and extended to cover additional diseases; more reliable estimates of heat-related mortality, especially in the future. Life tables to 2100.</td><td rowspan="3">Methods for extending risk factors and life tables are established. Heat related mortality may be difficult due to uncertain adaptation to higher temperatures.</td><td rowspan="3">1 to 3 years.</td></tr>
<tr><td>Life expectancy</td><td>The metric does not record information on the quality of life. Monetisation is feasible but can result in different values being placed on populations with different income levels. Aggregation can occur at a country level.</td></tr>
<tr><td>Deaths per thousand population</td><td>Not suitable for monetisation because the metric does not account for differences in life years or quality of life. Aggregation can occur at a country level.</td></tr>
</table>

Source: Vivid Economics

Table 10 Poverty indicators require research on extreme weather events and socio-economic development

Suggested indicators		Research needs of suggested indicators					
		Climate science			Socio-economic research		
Indicator	Valuation, monetisation and aggregation	Requirement	Feasibility	Time scale	Requirement	Feasibility	Time scale
Change in multi-dimensional poverty Change in number of households below a poverty line	The equity and life chances outcomes are valued by society as a whole. Difficult to monetise and probably not suitable for monetisation. Impacts may be highly localised, requiring indicators to be highly disaggregated.	Extreme weather events that affect agricultural output through heat and precipitation, or damage buildings and infrastructure through storms.	Current climate models could be used to estimate heat waves, droughts, flood events and storms.	Improved estimates of heat waves, droughts and floods in 1 to 3 years; up to 5 years for storms.	Impacts of weather-related disasters on dimensions on poverty, and of agricultural productivity on incomes for poor, agriculture-dependent households. Socio-economic scenarios to 2100 for low-income groups.	Considerable research would be needed to elicit these impact relationships.	1 to 3 years for income-related effects. Up to 5 years for education, health and services.

Source: Vivid Economics

Table 11 There is an absence of core information for ecosystem services and a modelling framework with limited data for biodiversity indicators

Indicator	Suggested indicators	Research needs of suggested indicators					
	Valuation, monetisation and aggregation	Climate science			Socio-economic research		
		Requirement	Feasibility	Time scale	Requirement	Feasibility	Time scale
Ecosystem services	Some ecosystem goods and services will be marketed or have marketed substitutes. Others will have to be valued through revealed or stated preferences. There are generic difficulties with stated preference techniques. Consequently, non-monetised metrics will always be important in the description of ecosystem services.	Expert advice should be sought.			Comprehensive, quantitative, assessment of current ecosystem services, future baseline scenarios and sensitivity to climate change.	Very difficult in global aggregate, but possible to obtain local examples for a sample of key biomes or services.	5 to 10 years.
Mean Species Abundance (MSA) loss	Difficult to value since the MSA covers a wide range of attributes, goods and services provided by ecosystems. It is unlikely that monetisation of this metric could ever be reliable. Aggregation is appropriate at a national, regional or global level.				Scenarios for pressures on biodiversity from population growth and economic development	Population and economic scenarios already exist but expert advice should be sought on the feasibility of relating these to the impact on biodiversity.	1 to 3 years.

Species at risk of extinction	Species extinction suffers from similar monetisation difficulties to the rest of ecosystems valuation. Namely, reliance on stated preference techniques and variation in attributes, goods and services between species. Monetisation is unlikely to ever be reliable.				

Source: Vivid Economics

Table 12 Agriculture and energy indicators are estimated with large uncertainties and climate science for extreme events is absent

Suggested indicators		Research needs of suggested indicators					
		Climate science			Socio-economic research		
Indicator	Valuation, monetisation and aggregation	Requirement	Feasibility	Time scale	Requirement	Feasibility	Time scale
Agriculture: Change in yield	Easy to monetise using market prices provided estimates of area of crop grown are known. Country-level aggregation is adequate.	The effect of CO_2 fertilisation remains highly uncertain. Estimates of changes in available water from precipitation could be improved.	Work is progressing on resolving issues of CO_2 fertilisation.	Improved estimates in 1 to 3 years.	Improved modelling techniques for global and consistent estimates across scenarios. Improved modelling of adaptation.	Modelling work is progressing, but large uncertainties are likely to remain hard to resolve.	Up to 5 years.
Agriculture: Change in output	Easily monetised using market prices. Country-level aggregation is adequate.						
Energy: Change in energy expenditure	Monetised via the market prices for the energy required to heat/cool environment. Aggregation at a country-level is suitable with a focus on households in energy poverty.	Current estimates of temperature change provide a scientific basis for this indicator.			Future technology and energy prices are required to monetise changes in heating and cooling degree days.	Future technologies could be mapped in 1 year but reducing energy price uncertainty is inherently difficult.	1 to 3 years.
Extreme weather: Damage to assets due to extreme weather	Damage can be monetised using insurance industry methods applied to all assets rather than just insured assets. As impacts will be local estimates could focus on	Understanding how climate change will transform the intensity, location and	Current climate models could be used to estimate heat waves, droughts, flood events and storms.	Improved estimates of heat waves, droughts and floods in 1 to 3	Estimates of asset loss will be needed in areas for which data is not currently available.	Mapping likely to be possible based on income, population, assets and studies of past extreme events.	1 to 3 years.

events	hotspots.	frequency of extreme weather events.		years; up to 5 years for storms.			

Source: Vivid Economics

Table 13 Coastal flooding is well-characterised, in contrast to fluvial flooding, which requires primary research

Suggested indicators		Research needs of suggested indicators					
Indicator	Valuation, monetisation and aggregation	Climate science			Socio-economic research		
		Requirement	Feasibility	Time scale	Requirement	Feasibility	Time scale
Cost of protection against changing sea levels	Monetised engineering estimates of protection such as sea walls. Aggregation can occur at any level from lengths of coastline to global.	Changes in storm surge heights have yet to be well characterised. This requires estimates of wind speed and force change.	Expert advice should be sought.		Exploration of imperfect information and increasingly realistic adaptation.	This is likely to feasible, given advances in adaptation decision making.	1 to 3 years.
Number of people flooded	The metric is a non-monetised indicator. Aggregation can occur at any level from lengths of coastline to global.				Accurate headcounts of coastal pop. are required because population tends to be concentrated on the coast.	Coastal population data is likely to be easy to determine, at least for the majority of coastal sites.	1 to 3 years.
Damage to assets due to fluvial flooding	Damage can be monetised using insurance industry methods applied to all assets rather than just insured assets. As impacts will be local estimates could focus on hotspots.	Precipitation at finer levels of granularity is required to significantly reduce the level of uncertainty of impact estimates.	Expert advice should be sought.		Geographic data to a fine level of granularity is required to estimate runoff. In particular the flow of runoff between cells is not widely modelled.	Detail of information and modelling effort required may be demanding.	Will vary by location; up to 10 years.
Number of people flooded	The metric is a non-monetised indicator. Focus could be on hotspots.						

Source: Vivid Economics

8 Conclusions

The original ambition for this project was to gather together and present a coherent picture of climate impact estimates over time, scenarios of development, states of nature and space. This was not fully achieved, despite the large body of evidence on impacts that has accumulated, and the advances in analysis that continue to be made. It is right to ask why it proved so difficult a task.

One reason is scale: it is an expansive area of academic endeavour, covering many sectors, geographical regions, scenarios of socio-economic development, ethical considerations and time periods. Another reason is that the systems involved are highly complex, non-linear and uncertain. A third reason is that not enough evidence has yet been collected by the research community. In addition, there is a fourth reason: the way in which existing information is presented makes its collation difficult.

Let us return to the question of what to do in response to the study's outcome after first considering why it is so important to build up a comprehensive picture of significant impacts.

When possible outcomes are as serious as those threatened by climate change, and the opportunities to avert damage so important to grasp, it would be hard to overstate the value of information which describes the scale, distribution and nature of those impacts. In the face of competing claims on budgets, scepticism in some quarters and a need to organise an adaptation response, this evidence is required to help build consensus.

The value of the information lies in policy decision-makers being able to rely upon it and in garnering support among the public for action to be taken. In order to play that role well, it is necessary to communicate the information to its various audiences in a way that is clear and credible.

A range of relevant metrics might inform the difficult policy decisions that may have to be made and support constructive debate in the court of public opinion. What makes a good metric? The answer might be that it measures something that matters, is meaningful, can be placed in context, is scalar, and allows comparison with other impacts, costs or benefits. One may observe that by no means all of the current metrics published satisfy these particular criteria.

It is reasonable to suggest ways forward and in setting out food for thought, it is appropriate to set the ambition level high. This is why the suggestions made here include challenging metrics such as life expectancy, multi-dimensional poverty and several dimensions of biodiversity, whose feasibility is uncertain. It would not be right to claim here to have found the best answers, but would be enough to prompt and frame a debate which experts can enjoin.

This study does not suggest steps by which the findings might be taken forward and challenged, but there are questions here to be answered: how might the suggested metrics be exposed to a wider audience, challenged, alternatives debated and feasibility tested? How might decision-makers establish a framework to deal with uncertainty?

Returning to the value of information, there is an acute awareness that timely information that may result in earlier action might be more valuable. Sufficient metrics are no use without sufficient information with which to generate them. It seems that the jigsaw of underlying information that would be needed for the metrics suggested here, and for some other metrics already in use, is incomplete. These are significant holes and the value created by filling them may prove to be very high.

Some areas stand out as priorities. They have been listed within the report in detail. The areas of social welfare of most concern are health, poverty and biodiversity. In terms of climate threats the priorities concern tipping extremes: extreme weather events. high temperature increases, worst and best case outcomes. Governments such as the UK have the resources, access to expertise, and political will to make a difference in some, but perhaps not all of these. They are already involved in, and are responsible for deciding the quantum of effort committed and its distribution, and have some responsibility for organisational efficiency.

It would be a natural next phase, to the extent it has not been done already, to address questions relating to research management, such as: What is the current rate of progress in assessing the impacts of climate change? Where do responsibilities for assessment lie, how is effort organised and how is it funded, not just in the UK, but within and among all major research players? Given the current arrangements, within what timescales are key results likely to become available? Might alternative ways of organising research and levels of funding deliver faster or more robust results? Would more coordination be better, and if so by what means and using what resources?