ECONADAPT

The Economics of Adaptation

Funded by the European Union

Task 3c: Methods for the assessment of systemic change

Authors: Jacob Wellman and Alistair Hunt

Deliverable number	3.3
Work Package Number	3
Submission date	25.4.2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Methods for the assessment of systemic change
Authors:	Jacob Wellman and Alistair Hunt
Other Contributors	None
Date:	25.4.2016
Contact details	Jacob Wellman (jake.wellman@gmail.com)
Work Package Number	WP3
Deliverable number	D3.3
Filename:	.doc
Document history:	Final
Type of Activity	RTD
Nature	R
Dissemination / distribution level	PU = Public
Citation:	Wellman, J. and A. Hunt (2016) Methods for the assessment of systemic change, Deliverable 3.3. EC DG Research ECONADAPT Project. Grant Agreement no 603906
Copyright:	Yes

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

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

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

.

Executive Summary:

Deliverable 3c “Methods for the assessment of systemic change”

This deliverable presents the problem of systemic risk in the context of climate change, reviewing the extent to which this concept is captured in existing tools used in the economic analysis of climate change and suggesting improvements to these tools. The analysis and suggestions from the deliverable are illustrated in an application examining the Syrian refugee crisis as an example of climate-induced migration.

Systemic risk is defined as a potential damage with repercussions that transcend national borders or require transformational adaptation. Economic literature has concentrated on market costs and to a lesser extent non-market costs, but costs stemming from systemic change, particularly those impacted by socially contingent responses to shocks, remain untreated. This deliverable attempts to provide some methods for addressing these latter categories of costs.

Section 2 of the paper reviews existing economic tools, including partial equilibrium models, general equilibrium models and methods of non-market valuation methods. The benefits of general equilibrium models are discussed, but with discussion of their limited ability to capture non-market values. Partial equilibrium models are presented as an option for illustrating non-market values, but without a broad capability to model impacts from non-marginal changes in a market. Integrated Assessment Models are also introduced as an economic modelling tool specific to climate change analysis.

Section 3 reviews the systemic risks expected from climate change, including tipping points events related to catastrophic climate change. The IPCC ranking of risks from climate change are reviewed as well as specific impacts of various tipping points such as the melting of ice sheets or interruption of homeostatic functions in the planetary ecosystem.

Section 4 presents an evaluation of commonly used economic tools in the context of systemic risk. Cost-benefit analyses are reviewed and questions around the accuracy of predicting non-market costs are presented. Methods for calculating the Social Costs of Carbon are detailed, with critiques of existing practices drawn from the literature. Integrated Assessment Model shortfalls are presented, as well as the socioeconomic pathways used in IPCC projections. Theoretical criticisms of the treatment of systemic risk are discussed, including Weitzman’s Dismal Theorem and alternative applications of discount rates based on risk and timeframe. Findings of the Stern Review on the Economics of Climate Change are presented, with specific attention to the amplification of damages in models when catastrophic climate change is considered.

Section 5 suggests strategies responsive to the issues discussed in the previous section, including recursive modelling in cost-benefit analyses that is responsive to developments in climate information. Ranged estimates for social costs of carbon are presented as one method for reducing uncertainty. Specific modelling corrections are summarised from the literature, including those suggested for DICE and PAGE models. Ethical considerations are discussed along with methods for addressing these concerns quantitatively, chiefly through premia in carbon tax rates, and qualitatively—by prioritising the needs of the populations most impacted by climate change.

In an application section, the recommendations from Section 5 are contextualised for the ongoing refugee crisis stemming from Syria. General background on the economics of migration and the connection between climate change and human migration are reviewed and details of the Syrian crisis are summarised. Scientists have shown a connection between extreme drought conditions and conflict in the region. Costs stemming from migration, including those to both migrants and destination countries, as well as non-market costs that are difficult to quantify. Available information on the volume of migrant flows to various countries and the refugee-related expenditures are presented to provide a snapshot of the costs of a systemic event related to climate change. Strategies presented earlier in the paper are presented in the context of the migration scenario, model improvements, scenario pathway analysis and maxi-min policies are all presented as analytical approaches to manage similar risks over the future.

Table of Contents

1 INTRODUCTION 7

1.1 DEFINING SYSTEMIC RISK 7
1.2 RESPONDING TO SYSTEMIC RISK 8

2 EXISTING ECONOMIC TOOLS 9

2.1 PARTIAL EQUILIBRIUM MODELS 10
2.2 GENERAL EQUILIBRIUM MODELS 11

3 SYSTEMIC RISKS FROM CLIMATE IMPACTS 14

3.1 CLIMATE TIPPING POINTS AND FEEDBACK LOOPS 14

4 MODERN TOOLS AND SYSTEMIC RISK 16

4.1 COST BENEFIT ANALYSIS 16
4.2 ACCOUNTING FOR CATASTROPHE WITH THE SOCIAL COST OF CARBON 17
4.3 INTEGRATED CLIMATE MODELLING 17
4.4 THEORETICAL TREATMENTS OF SYSTEMIC RISK 20
4.5 THE STERN REVIEW 21

5 ALTERNATIVE APPROACHES TO WEIGHING SYSTEMIC CLIMATE RISK 23

5.1 IMPROVING CLIMATE MODELS 24
5.2 SYSTEMIC RISK AND ADAPTATION 25
5.3 PRIORITISING THE WORST-OFF 25
5.4 STRONG SUSTAINABILITY 25

6 APPLICATION: THE SYRIAN REFUGEE CRISIS 28

6.1 MIGRATION AS TRANSFORMATIVE ADAPTATION 29
6.2 MODELLING THE ECONOMICS OF MIGRATION 29
6.3 ALTERNATIVE APPROACHES TO ECONOMIC MODELLING OF CLIMATE MIGRATION 30
6.4 A CLIMATE RISK MANAGEMENT VIEW OF THE SYRIAN REFUGEE CRISIS 31

7 CONCLUSIONS 36

8 REFERENCES 37

1 Introduction

Impacts from climate change span economic and social elements. Integrated models predict how changes in temperature, precipitation and ocean dynamics may translate to physical damage from sea level rise, flooding, drought, which in turn can be valued in monetary terms. In aggregate, these damages can have broader impacts on societal systems such as mass relocation stemming from property damage, agricultural system disruption or the spread of tropical disease to new territory (King et al, 2015). Existing models allow for valuation of predicted local impacts by applying non-market valuation techniques to anticipated physical changes resulting from a given change in climate in order to derive costs of damages to natural and human capital. However, these tools rarely consider low-probability but high-impact catastrophic events that may result from climate change (e.g., glacial melting, thermohaline current shutdown) or network effects in addition to aggregate domestic costs. These additional impacts threaten to "multiply existing threats" up to an order of magnitude greater than domestic threats alone (Geldhill et al, 2013). This paper reviews current economic tools used in analysis of climate risks, evaluates their ability to capture catastrophic and systemic effects, and reviews alternative approaches and frameworks.

1.1 Defining systemic risk

The projection of costs and damages from climate change is commonly generated from integrated geo-economic models that produce useful results for national damage assessments based on costs from physical damages in sectors across a geographical region (examined more closely in Sections 2 and 4 herein). However, transnational and international impacts may bring substantial changes in welfare to individuals that are not captured by models that use country-level analysis as a reference point. Systemic risk encompasses those impacts from climate change that create changes in welfare greater than those predicted by direct and indirect impact models, due to changes in a system caused by a shock in one area that impacts other specific areas or the entire system (e.g. shocks to food prices caused by extreme weather events or food scarcity). System-wide risks may also result from the possibility of highly uncertain, but catastrophically damaging "tipping point" events occurring, such as the melting of large ice sheets or the interruption of bio-regulatory processes that keep planetary life support systems stable (discussed in Section 3). These catastrophic impacts are excluded from many economic analyses of climate change due to methodological questions, including those around expressing the uncertainty of when and how these events may occur.

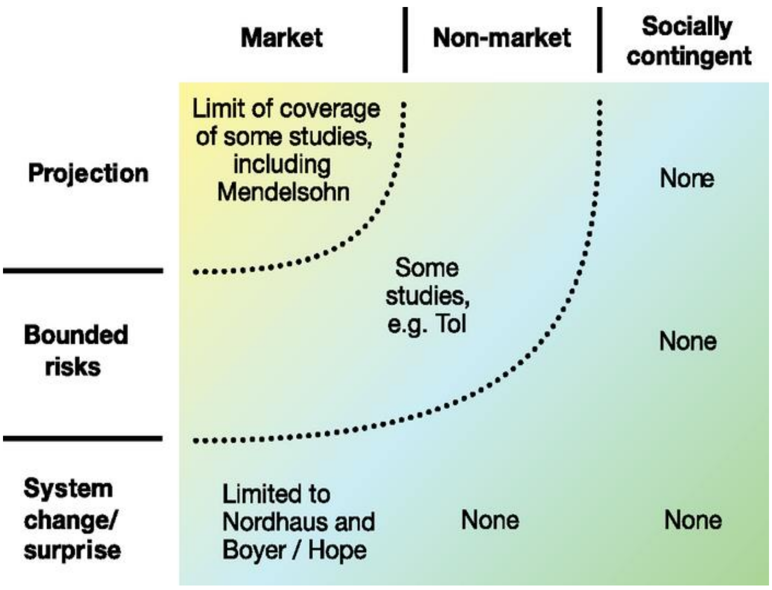
While the treatment of systemic risk in economic evaluation of climate change is still developing, others have developed methods to address this type of risk. Their examples may prove helpful for climate economists. For example, the European financial community has identified systemic risks from climate change to financial assets around the continent, using scenario analysis to anticipate the worst possible outcomes in the financial sector. Three parts of systemic risk to financial system include: 1) macroeconomic impact of sudden changes in energy use (shifts to alternative sources, increases or decreases in aggregate demand or supply—similar to the impacts seen in the 2015/2016 drop in the price of oil); 2) the revaluation of carbon-intensive assets (i.e., stemming from a carbon price); 3) increase in natural catastrophes (European Systemic Risk Board, 2016). The third category is the impact of most interest for communities concerned with adaptation to climate change.

1.2 Responding to systemic risk

When faced with systemic risk, societies have two options with which to respond. The first of which is the primary focus of this paper: managing systemic risk by incorporating it into economic analysis tools. Where risk cannot be managed, either because analytical tools cannot be improved to incorporate systemic risk or where risk has manifested into catastrophic climate change, transformative adaptation may be the only response available. The second—transformative adaptation—encompasses efforts to respond to impacts greater than those that incremental adaptation efforts seek to address. Transformative adaptation might include changes in social or governance structures to implement policy responses, migration or geo-engineering schemes (O'Brien, 2012).

Uncertainty is a topic core to the discussion of climate change and its projected impacts. The state of knowledge when it comes to accounting for various levels of uncertainty from climate change in economic models has been developed in depth over recent years, but some gaps remain, particularly in respect to quantifying impacts from system changes, non-market value disruptions and socially contingent risks, as shown in Figure 1. In this representation, "socially contingent" risks refer to the potential for longer-term or catastrophic events, the outcomes of which are determined by social reactions to climate impacts that cannot be reliably anticipated with currently available information (Watkiss et al, 2005). Some examples of these broader risks include costs at the international level, collapse of social structures on a regional scale and irreversible losses in e.g. ecosystems.

Figure 1. State of knowledge around risks measurement



(Watkiss et al, 2005)

2 Existing economic tools

Economists assign value by measuring changes in welfare resulting from a specific policy or programme. These changes are estimated by modelling specific markets as well as the wider economy. Economic changes are often modelled in partial and general equilibrium, the former most commonly providing an up-close perspective on the interaction between two goods/services while the latter predicts how the wider economy will respond to a shock in a particular sector. Non-market valuation techniques are used to derive values for goods and services not traded on the market. Many of the largest impacts threatened by climate change fall in this category and an understanding of these methods is essential to critically evaluate the effectiveness of economic tools in analysing climate risks. Table 1 summarises the advantages and disadvantages of each of these approaches common to economic modelling.

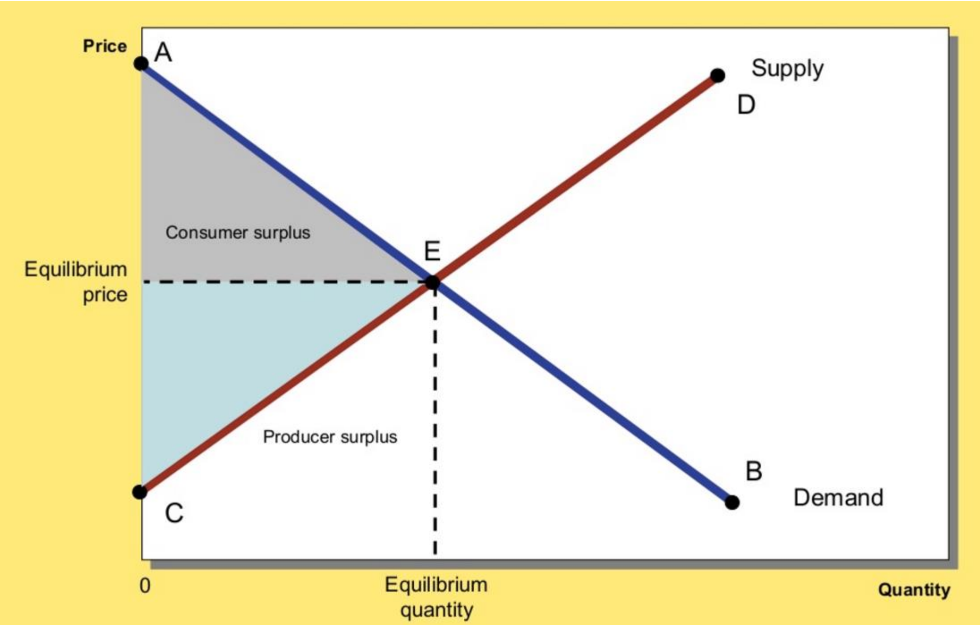
Table 1. Economic tools for climate valuation

Partial Equilibrium Models	**General Equilibrium Models**
Market-Based	Market-Based
• Illustrates impact on price for a given product from changes in quantity of price of another • Models demand and supply in constrained market of interest • Provides information on marginal changes	• Interactions between sector, elasticities included • Full economy modelled • Non-market goods generally excluded from modelling • Often assumes static picture of economy, not accounting for endogenous growth
Non-Market	Non-Market
• Cost Benefit Analysis framework facilitates trade-offs by using common monetary metric • Stated Preference and Revealed Preference methods used to capture these values) • Social Cost of Carbon used to represent aggregate costs from emissions • Potential biases and concerns around valuing non-market goods	• General equilibrium models do not include non-market goods/services

2.1 Partial equilibrium models

Impacts on individual markets are estimated in *partial equilibrium* models, which attempt to illustrate changes in production, consumption and utility resulting from a change in input or preferences within the same closed market. The rules governing partial equilibrium include a balance of supply and demand in relation to the price and cost of a given good. These models demonstrate amounts of producer and consumer surplus from a given price point—utility is gained when a producer sells a good for a higher than a minimum acceptable price and when a consumer purchases a good for a price lower than the maximum (see Figure 2).

Figure 2. Consumer and producer surplus



(Mankiw et al, 2002)

In such a constrained model, where a single product is analysed, an increase in cost of a product is likely to lead to an increase in price and a resulting decrease in the quantity sold of a good. Similarly, technological advances could lead to lower production costs, driving down the price of a good and spurring an increase in the quantity sold. These production-side effects on a market are important to consider with climate change as changes in costs of raw materials and other inputs are likely to accompany predicted changes in the climate (Chambwera et al, 2014). Production is also likely to benefit from technologies developed under climate policy, such as cheaper energy sources or more efficient buildings. Demand-side factors are also important to consider for climate change policy. Consumer preferences may shift with the development of better substitutes or increased aversion to pollutants or risk. New product purchases may bring increased demand for complementary goods. Income changes resulting from physical damage wrought by climate change may change which products consumers can afford.

Within partial-equilibrium models, products not sold in markets can be represented using non-market valuation techniques, known as revealed and stated preference methods. Non-market goods, such as physical well-being or environmental quality, retain value for individuals even if they are not readily available in exchange for an individual’s money (Perman et al, 2003). These methods are often used to value public goods that are protected or provided by a central government authority, rather than by individuals in a market setting. Surveys and observations indicate that individuals are often willing to pay a given monetary amount for these goods. By illustrating trade-offs between monetary amounts and non-market goods, these studies derive a value for non-market goods that can be compared to market goods. Estimates of these values can be aggregated to derive a total value for a non-market good. The most commonly used techniques are outlined below.

- Stated preferences: this method asks individuals through scientific surveys to state their preferences in monetary terms for a non-market good, or choice between several goods. Surveys may ask how much a respondent would be willing to pay to preserve a hectare of green space near their house, or what an acceptable increase in their water bill would be for clean water. Choice experiments have also proven an effective method of measuring value. These surveys present a package of different non-monetary goods, monetary amounts, and regulatory measures to measure how individuals value goods through making trade-offs (Bennett & Blamey, 2001). Stated preference valuation can result in errors from a number of biases related to the quality of information presented to respondents and the perception that their response will have actual monetary or policy impacts.

- Revealed preferences: this method attempts to extrapolate economic value for a good based on observed behaviour. The Travel Cost Method measures the costs incurred by individuals to travel to an unvalued asset, such as a recreation area or national park. Avertive expenditure studies estimate the value ascribed to maintaining health by measuring expenses on preventative care. Hedonic valuation techniques derive preferences for non-market attributes by studying the relationship between an occurrence of an unmeasured good (i.e., proximity to a riparian zone) and a comprehensive measure of value, such as real estate prices. These methods have the benefit of reflecting actual expenditures, thus avoiding the hypothetical bias of stated preference methods, but may fall short of capturing the total consumer surplus of a non-market good. This could result in undervaluation of public goods and lead to suboptimal policy decisions.

Integrated Assessment Models currently used to project climate impacts under various emission and socioeconomic scenarios rely in part on partial equilibrium analysis to model effects on a particular sector. Examples of partial equilibrium models used in the construction of shared socioeconomic pathways (discussed in Section 4.3) include FUND, GCAM and IMAGE/TIMER (IIASA, 2015). The Stern Review applied the PAGE model, which also uses partial equilibrium techniques. These models are able to provide information on a specific sector, but may lack information on how sector changes affect other areas of the economy. Excluded cross-sector impacts are likely to include elements of interest to systemic risk managers. Additional analysis may be necessary for policy decisions relying on partial equilibrium models to assess total impacts from a given action, hence the potential use of general equilibrium models.

2.2 General equilibrium models

For macroeconomic models examining impacts on the full economy, economists often use a general equilibrium model. In the general equilibrium model, multiple markets are modelled in aggregate, accounting for interactions between markets and elasticities to price changes.

These models are built with complex software that model interactions in the wider economy. Aggregate production for a country is measured by Gross Domestic Product, (GDP), in these models, a figure of national wealth calculated by summing the value-added by each step of producing goods in a country, plus tax revenue, minus subsidies. Growth in GDP is the primary measure of economic success at the national level, though aggregate measures of wealth can mask significant changes in sectors or groups within a country. Excluded from GDP, non-monetary values such as environmental goods and services and indirect health costs are still important considerations in policy. Similarly, catastrophic climate impacts not valued in existing markets are absent from these models.

General equilibrium models inform much of the shared socioeconomic pathways (SSP) analysis used to model climate change over various versions of a future world. AIM/CGE, MESSAGE-GLOBIOM, REMIND-MAgPIE and WITCH-GLOBIOM are all general equilibrium models included in SSP modelling, while DICE is a general equilibrium model used in setting the social cost of carbon by the US government (IIASA, 2015).

Both partial and general equilibrium models are important in modelling the economic impacts of climate change, but each offers only incomplete coverage in assessing socioeconomic effects from physical changes in climate. Partial equilibrium models are useful for estimating the impacts on a particular market from a change in an input or complement, especially those concerning non-market goods. However, partial equilibrium models are restricted to showing marginal changes in markets that provide a limited perspective on impacts in the wider economy from a given change. Conversely, general equilibrium models can model complexity across markets, but are limited in their ability to account for preferences towards non-market goods, which can have important social and ethical implications, as discussed herein. While some Integrated Assessment Models (IAMs) incorporate general equilibrium models to assess socioeconomic impacts of climate change, many of these models fall short of capturing non-market welfare impacts such as social and political instability, cross-sectoral and dynamic impacts (Stern, 2006). The Stern Review suggests that these shortfalls lead many IAMs to substantially under-estimate the costs of climate change impacts and adaptation.

A type of model that attempts to introduce a greater degree of realism to the representation of climate change risks is the non-equilibrium dynamic model ((NEDyM) Hallegatte 2007). This type of model is concerned with the improved modelling of instances where markets do not clear (reach equilibrium) quickly. This is likely to be the case, for example, where supply does not meet demand following an extreme weather event that results in business disruption and supply chain disruption, and where prices are sticky downwards. More generally, this type of model serves to show how the impacts of extreme weather events on economic capital will bring about consequent indirect effects on both the demand and supply sides of the economy, as the condition of general equilibrium is relaxed.

A prominent sub-set of this non-equilibrium model is input-output analysis. Input-output analysis is based on the fact that in modern economic systems linkages exist between activities. Each production activity acts both as a “supplier” and a “buyer”: Input-output analysis is essentially a method of systematically quantifying the linkages between various sectors in an economy. The assumptions underlying the construction and operation of input-output models are sometimes subject to criticism. For example, it is not always the case that fixed coefficients (assumed in many input-output models) accurately describes real production relationships, especially when non-marginal changes in output are anticipated. Nonetheless, one of the questions we are trying to answer when faced with general equilibrium effects is, what are the channels by which a change in impact (or response) directed at one market affects behaviour in other markets? Input-output tables can prove very useful in answering this question. An example of its application is the study undertaken by Hallegatte (2008) on the economic impacts of Hurricane Katrina in Louisiana, USA. The model takes into account changes in production capacity due to productive capital losses and adaptive behaviour in the aftermath of the hurricane. In this context, the assumption that markets do not instantly clear – a consequence of having fixed coefficients of production – is appropriate in the period of a few months after the storm event. The study finds that economic processes exacerbate direct losses, and total costs are estimated at $149 billion, for direct losses equal to $107 billion.

3 Systemic risks from climate impacts

The IPCC's Fifth Assessment Report summarises the current science on the impacts of climate change, including systemic risks and catastrophic shocks. Among the interruptions to existing systems threatened by climate change, agriculture and water supply are endangered by losses in biodiversity that are highly likely to result from an increase in global temperatures. Agricultural systems face severe disruption from a decrease in pollinator populations and losses in soil from extreme weather events and shifting precipitation patterns. Of particular concern are areas where these systemic impacts combine with other climate risks. These include island nations and coastal areas where property loss from sea-level rise, decreasing fishing yields and agricultural disruption all contribute to highly disruptive conditions in the future (Oppenheimer et al, 2014).

Similarly, market responses to physical climate change may exacerbate economic costs. Economic feedbacks such as rising food prices in response to scarcity created by physical change can amplify food scarcity. Ocean acidification and rising water temperatures will reduce production in fisheries, and could lead to overfishing and collapse of fish stocks, causing high unemployment in communities dependent on fishing industries (ibid.).

Risks to human health and security may also be compounded by responses to other climate impacts. Migration resulting from displacement and conflict over land and natural resources both stand as significant sources of risk from climate change. Health effects are likely to increase from malnutrition stemming from food insecurity, increased production in pollen and other allergens from climate change. Climate impacts are expected to most seriously affect areas with weaker governance structures, increasing the anticipated damage from systemic shocks such as resource scarcity, economic disruption and serious risks to human health (ibid.).

Climate change may also have a significant poverty trap effect, though the size of this effect is uncertain (Tol, 2015). Higher morbidity rates and lower crop yields stemming from climate change will reduce labour productivity, which in turn will depress savings levels and reduce investment in capital, slowing the growth of developing economies. Infant mortality could also lead to a rise in childbirths, spreading thin spending on education and healthcare for young children and slowing growth in human capital.

Tol (2015) shows that the economic impacts of climate change are partly determined by a country's income and average temperature. Income serves as a buffer, with richer countries suffering less extreme negative impacts than poor countries, while temperature increases the impacts of warming—warmer countries are likely to experience greater effects from an increase in temperature. Thus, poor countries in warmer areas stand to experience the worst impacts from climate change in terms of GDP loss.

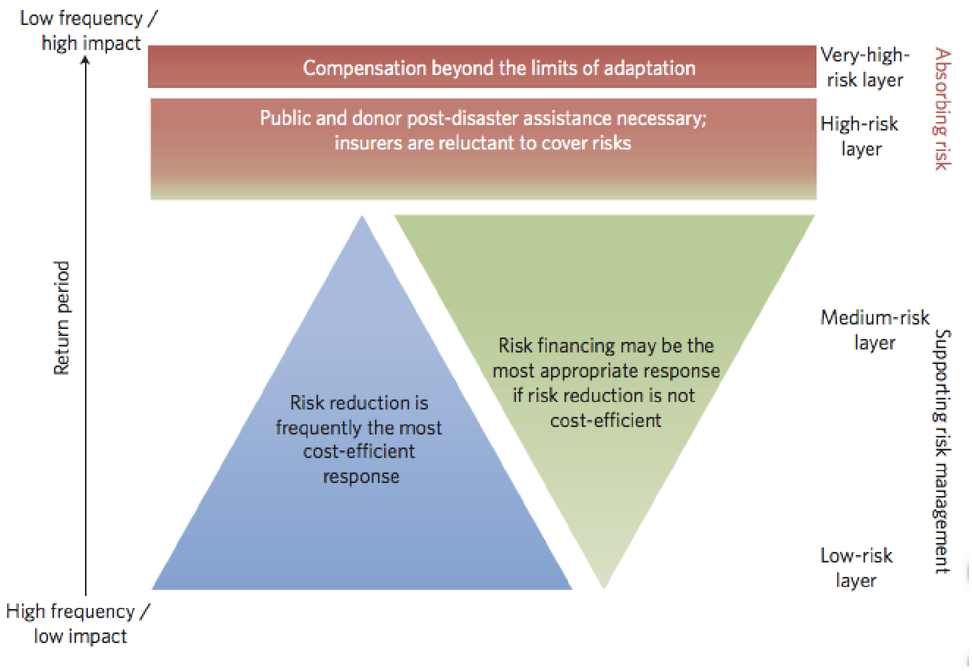
3.1 Climate tipping points and feedback loops

In addition to systemic and compounding socioeconomic impacts from climate change, major feedback events—known as *tipping points*—are expected to cause abrupt and significant climate change once certain temperature thresholds are reached (Lenton et al, 2008). These exact thresholds are not known, but any consideration of climate risks without tipping points cannot be complete. These tipping points comprise of major changes to geographical regions that lead to sea level rise, shifts in precipitation patterns or reduction in the planet's ability to process greenhouse gas emissions. The melting of permafrost and tundra is also seen as a climate feedback, as methane is released when permafrost melts, increasing warming effects in the atmosphere. Comparisons of predicted changes to observed impacts in the climate reveal a conservative bias in IPCC and other projections, with reported values of probability and climate sensitivity trending toward the lower end of probability distributions (Brysse et al, 2013). This bias may under-represent the risks posed by tipping points to the global climate.

Guillerminet and Tol (2008) show how consideration of tipping points should lead to a change in climate policy. In the case of the collapse of the West Antarctic Ice Sheet, damages from this tipping point bring forward the date of necessary emissions reductions, but once the tipping point is reached, the optimal policy path requires redirecting resources to adaptation efforts. Similarly, dieback of the Amazon rainforest is a high-consequence impact that should be counted among irreversible damages from climate change once temperature thresholds are reached. Because of the large uncertainties around these tipping points, there are varied practices used in some economic assessments to incorporate these catastrophic risks.

Responses to risk are developed through a layered disaster-risk management framework, as outlined by Mechler et al (2014) presented in Figure 3 below. This treatment organises responses into managed and absorbed risks, the former used to offset high frequency, low-impact risks. Systemic risks stemming from catastrophic tipping points are likely to reside in the top layer of the disaster risk management framework (see figure 3), essentially outside the realm of common risk management.

Figure 3. Disaster risk management framework



(Mechler et al, 2014)

4 Modern tools and systemic risk

Assessing economic tools for their ability to cope with high-consequence climate impacts requires a close look at how welfare economics has dealt with systemic risk to date. Economists have incorporated systemic risk into large-scale economic assessments based on geospatial climate models, adjustments to discount rates used in calculating costs and benefits over long time horizons and alternative assessments of damage from climate change. Concerns regarding the shortfalls of modern economic tools in accounting for risks of catastrophic climate change impacts range from concerns of inaccuracies in modelling future impacts to critiques of theory underpinning the treatment of future values over long time horizons. A broad sample of practitioners yields caution in interpreting model results literally, instead using these tools to predict trends and raise areas of concern for further investigation (Dietz et al, 2007; Weitzman, 2001; Beckerman & Hepburn, 2007).

4.1 Cost benefit analysis

Cost benefit analysis (CBA) is used by governments and businesses to measure return on investments for policies, projects and programmes. In its simplest form, CBA sums the total costs of a project, including construction, operation and any secondary costs from e.g. disruption, displacement or pollution and compares this aggregate value to the benefits resulting from the project, typically consisting of revenue, services valued by the public or consumers or avoided future costs. A specific form of CBA, social cost benefit analysis (SCBA), takes into account the costs and benefits to society from a particular action. This tool helps policymakers to value projects that improve social welfare across large populations, revealing benefits in aggregate that may not be readily apparent from an individual perspective. As a publicly-oriented tool, SCBA relies on non-market valuation techniques discussed above to capture preferences for environmental and social goods that are not easily priced on the market. SCBA is widely used amongst the governments of the world, but faces criticisms on ethical and practical grounds. In this paper CBA will be used to refer for all types of cost benefit analysis, including social applications.

CBA converts social impacts into monetary values in order to compare different consequences from policy alternatives. The use of monetary value as a proxy for social welfare excludes consideration of diminishing marginal utility of income, which can vary significantly across economic strata of society (Layard et al, 2007). Cross-country comparisons of happiness surveys over time yield an elasticity of income of 1.24, showing that individuals at the lower end of income distributions derive more utility from each dollar than higher income peers. Similarly, when comparing projects across countries, differences in wealth and income between countries may distort CBA comparisons if not adjusted to reflect national differences. Within societies, CBA is often silent on distributional impacts of policies across income and demographic groups (Atkinson & Mourato, 2008).

When applied to climate adaptation projects, CBA methods can become further complicated. CBA structures have been relied on to communicate risks related to policies by inputting expected values of damages. When these expected values have high uncertainties, as in the case of catastrophic climate change, there is no reliable method to represent such uncertainty within the CBA framework (Hultman et al, 2010). Because CBA aggregates risk as one piece of a larger cost, nuanced uncertainty around outcomes and damage is difficult to represent in a single numerical output.

A separate concern with the representation of risk in CBA methods is around the type of risk included in CBAs. Costs can be represented as individual loss or as impacts to a larger social body. Individual damage can be measured with the use of statistical life values or health damages in DALYs, but these estimates do not provide a complete account of damage from a particular event. For example, estimates of the impact of the 2010 Superstorm Sandy on the United States include direct property and life damage as well as a formula of disruptive impacts to represent indirect costs (Kunz et al, 2013). In this study, indirect costs were calculated as a sum of business interruptions, power blackouts and transportation disruptions. These represent an advanced analysis of impacts on commerce from the storm, but non-commercial factors such as disruptions to children's education or healthcare provision to the infirm are much harder to measure. Given the difficulties representing complete costs retrospectively, inclusion of indirect costs from catastrophe for future events appears extremely difficult. CBA is also generally limited to partial equilibrium analysis which makes these costs types difficult to capture.

4.2 Accounting for catastrophe with the Social Cost of Carbon

Within a monetised CBA approach to project valuation, environmental costs are calculated using non-market valuation techniques. As an example, the Social Cost of Carbon (SCC) is used to represent the marginal aggregate effects of carbon emissions through climate change. With a set per unit value for carbon emission damage, evaluators can account for climate risks in project level appraisals. A project alternative that emits a high amount of emissions that would otherwise pass a cost-benefit comparison may look less optimal if the correct carbon price is included in the analysis. In practice, there is much disagreement on the optimal carbon price. In 2015, actual carbon prices across the world range from less than \$1 per ton of carbon dioxide emitted to \$130 per ton carbon(World Bank Group, 2015). Anthoff et al (2008) examine social costs of carbon across a range of risk aversion and discount rates, finding an optimal price of over \$200/tCO_2e.

Van den Bergh and Botzen (2015) show through a survey of estimates for the Social Cost of Carbon (SCC) that catastrophic climate change events are often not included in these values that shape climate policy across the world. Amongst values unaccounted for or partially represented in SCC calculations are the costs of biodiversity loss, political instability, violent conflict, large-scale migration, and effects on economic growth. These systemic effects are likely to represent additional costs if included in SCC models, suggesting that values used in policy formulation may underrepresent the costs of climate change to society.

When extreme climate events are included in models used to generate SCC values, they are calculated at probabilities determined by the modeller, not a scientific estimation. Debate on how these values are included in SCC calculations concern whether to apply Weitzman's Dismal Theorem (2009), which would stress damage from high-impact events at high temperatures, increasing SCC values by up to 420%. Including tipping points would drastically alter SCC values, and uncertainty levels associated with these risks are typically considered to be above politically acceptable levels. Where they are excluded from models and calculations, careful attention should be brought to the risks posed by tipping points. This is one of the most controversial issues in the calculation of climate impacts and continues to be of great concern.

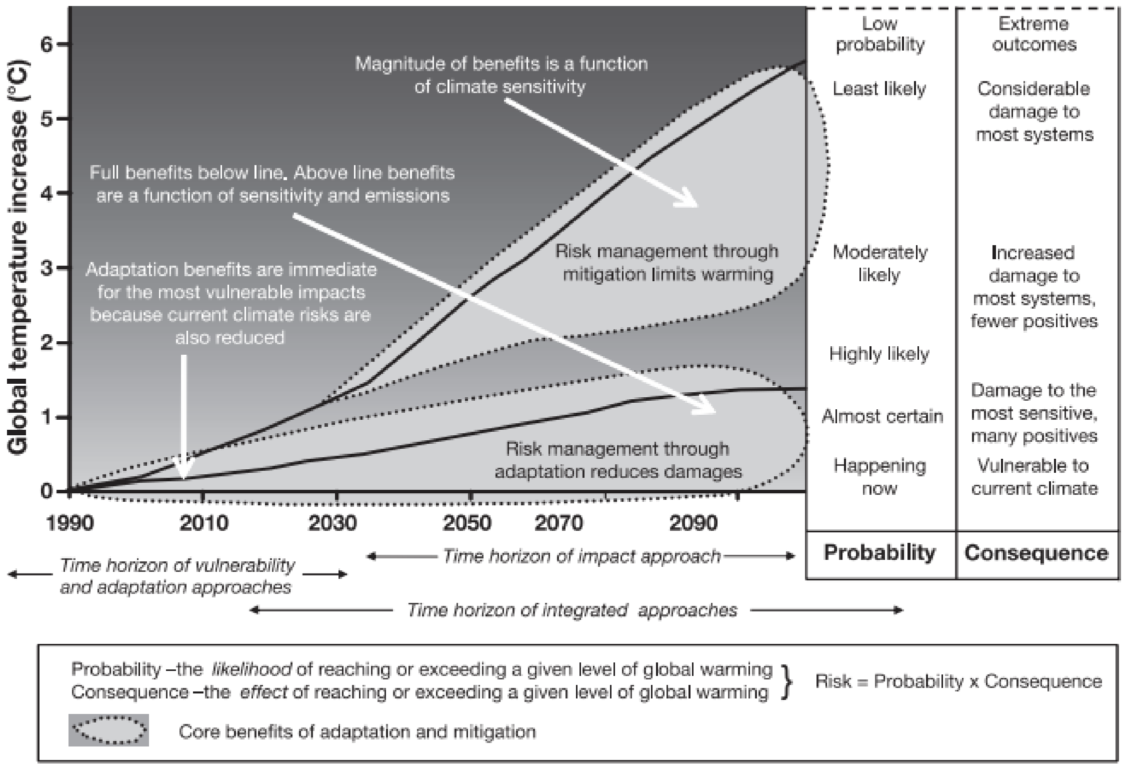
4.3 Integrated climate modelling

Emissions projections and resulting physical and economic responses to emissions are key determinants in setting climate policy. Improving the accuracy of models built to predict emissions growth and economic impact is a key area of work in the field. This subsection discusses the logic of these models and introduces some of the controversies currently debated in the field.

To manage multilevel uncertainty in climate predictions, scientists and economists have built complex models of predicted physical changes in the atmosphere and the ocean from increased stocks of greenhouse gases. Atmosphere-Ocean General Circulation Models (AOGCMs) present predicted changes in temperature and precipitation from expected climate change. The findings of these models are accepted with high certainty for large regions of the globe, but experience greater difficulty in predicting accepted impacts over smaller geographic areas. Confidence has grown in AOGCMs as computing power improves and inaccuracies are corrected over time. An important area of uncertainty in these models is in the impacts on climate sensitivity (the global average surface temperature increase resulting from a doubling in CO2 equivalent emissions into the atmosphere) from feedbacks in the climate system—particularly around the albedo effect of polar ice. Depending on the forcing effects of polar ice, melting ice caps could expedite temperature increases beyond what current models have suggested. A paucity of observed dynamics of ice caps has contributed to this uncertainty (Randall et al, 2007).

Findings from AOGCMs are fed into Integrated Assessment Models (IAMs), which aim to measure the impacts of physical changes on economic and social systems across mitigation, adaptation and vulnerability reduction efforts. These integrated models aim to capture interactions and feedbacks between multiple drivers and impacts and often rely on cross-sector information. IAMs are strengthened by analysis in other areas, such as the Millennium Ecosystem Assessment (2005), which identified climate change as one of many pressures on the world's ecosystems. Within this framework, risks are identified and then analysed before countries develop a responsive climate mitigation and adaptation policy response. However, the IPCC's 4th Assessment Report cautions that limits in predicting major tipping point events may handicap risk management strategies, as deep uncertainties in the impacts from these events are often excluded from damage calculations (Carter et al, 2007). Warning that such catastrophic impacts as the cessation of the Atlantic Meridional Overturning Circulation and the melting of large ice sheets in polar regions are often excluded from socio-economic models and thus risk prioritisation exercises, the IPCC calls for the development of risk management systems that can quickly respond to early warning systems of catastrophic change.

Figure 4. Risk management approaches to climate change



(Carter et al, 2007)

Modelling potential responses from society to climate change is a useful exercise as societal behaviour can significantly affect future climate change impacts and vulnerability. The IPCC relies on scenario-based models to illustrate different response paths to climate change. Four *Representative Concentration Pathways* (RCPs) were developed by researchers to represent different bundles of socioeconomic assumptions and accompanying emission patterns between 2000 and 2100. *Shared Socioeconomic Pathways* (SSPs) were concurrently developed to represent reference cases for how communities may develop in the absence of climate change (O'Neill et al, 2013). SSPs are formulated by combining assumptions of challenges to mitigation and adaptation efforts. The "best-case" pathway—known as SSP 1—assumes strong sustainable development efforts progress and little need for adaptation to climate change appears. Alternatively, the "worst-case" pathway, SSP 5, sees slow low-carbon innovation and high vulnerability to climate impacts around the world. Other pathways represent various combinations of mitigation and adaptation challenges. An important factor across pathways is whether innovation occurs globally, which technology shared and development supported across countries, or regionally, with certain areas benefitting from sustainable development but other remaining vulnerable. Economic growth also plays an important role in differentiating pathways: low growth slows innovation and increases vulnerability, whereas economic productivity is seen to increase mitigation technology development and adaptive capacity.

Though models are the primary tools available to guide climate policy, uncertainty accompanies advances in modelling. A collaborative report produced by climate experts in China, India, the UK and US reviews the shortfalls of modern modelling technology, counting scientific uncertainty, modeller subjectivity, and omitted variable bias among concerns around the state of the art (King et al, 2015). Integrating models to generate additional information may increase uncertainty in model outputs (Falloon et al, 2014). The appropriate level of model integration remains a goal for future research.

The envelope of models used to analyse climate change has contributed much to the world's understanding of risk posed by climate change. While predictions have become more certain over time, recognition of the shortfalls from ambiguity and uncertainty in climate models has impacted public policy. In the 2015 Paris climate conference, a 'High Ambition' coalition of countries organised by the United States led a successful campaign to call for a more ambitious mitigation target than was previously agreed. This unforeseen outcome is reflective of nervousness amongst world leaders that climate models may underestimate the planet's climate sensitivity and that drastic impacts may result from even ambitious attempts to check emissions.

4.4 Theoretical treatments of systemic risk

Major climate events, such as melting ice sheets and halted ocean currents, are thought likely to cause a great amount of disruption in socioeconomic systems around the world. Calculations of costs and benefits are structured to value costs from climate impacts differently based on when in time, and specifically how far into the future, they occur. The lack of certainty around when major threshold events might occur undermines this approach to calculating net present value. Economists have debated how to treat these long-term problems within the standard discounting framework. For example, Gollier, et al (2008) prescribe a menu of declining discount rates as policy time horizons extend to 400 years. In an aptly named 'dismal theorem', Weitzman suggests these high-impact events cannot be reliably represented in discounted economic cost models because of 'structural uncertainty' in assessing the likelihood of catastrophic events (Weitzman, 2011).

The dismal theorem is primarily concerned with uncertainty around *when* a catastrophic impact might occur. Nordhaus (2011) tests this concern, showing that the suitability of CBA for catastrophic climate change is dependent on 1) knowledge of the level of uncertainty around a given impact and 2) the relative risk-aversion of the population affected. In sum, "our standard tools of economic analysis are in deep trouble either when risk aversion or when the tail [of the probability distribution for a catastrophic impact] is very high" (ibid.). Grounded in the nature of how climate models are used, Nordhaus proposes that robust and qualified economic analysis continues to be useful in deciding a policy where the options are 'yes' or 'no', rather than attempting to calculate an exact valuation of the disutility caused by a given catastrophic risk. Instead of supporting a wide acceptance of Weitzman's dismal theorem, he encourages the continued inclusion of learning in decision-making tools, with constant updates to models and careful discussion of potential impacts rather than reliance on an unexplained CBA ratio.

Concerns about the shortfalls of CBA as an economic tool led Bosello et al (2005) to show that typical methods used to value health effects fail to capture important indirect effects of health impacts. Direct costs of health impacts are represented using a measure of costs that includes losses in labour productivity, demand for health care and resulting loss in GDP. The effects on prices from climate-related health impacts are negative across most countries and sectors, a result of a rebalancing of economies around health services industries and a decrease in labour productivity.

Climate change impacts - and efforts to mitigate them - can have large effects on national economies. As such, values related to these impacts may be non-marginal—causing cross-sector shifts in prices and preferences. If this is the case, standard marginal assumptions of constant consumption will produce distorted model results. Non-marginal impacts may be captured in general equilibrium models, whilst CBA analyses for national and regional projects may require detailed projections for future consumption trends such as those implicit in the SSP quantifications (Dietz & Hepburn, 2013).

4.5 The Stern Review

The 2006 Stern Review conducted for the UK government stands as the most comprehensive review of the economic costs and benefits of climate change. This review used the PAGE2002 model, an IAM that overlays predicted changes in the planet's atmosphere and oceans with a partial equilibrium economic model. Table 2 shows how the Stern review factors in additional economic damages from catastrophic risk and non-market impacts.

Catastrophic threats raise the percent of consumption lost from climate change by 3% in the mean case. The most inclusive run of this model includes considerations absent in most assessments such as distributional impacts and dynamic feedbacks from increased climate sensitivity. This inclusive run projects a drop in per-capita consumption of 20% over the next two centuries (Stern, 2006). To calculate these results, the PAGE2002 model was run through a 'Monte Carlo' simulation over a large number of potential parameter values, outputting a probability distribution of impacts, in an effort to account for uncertainty in particular parameters (i.e. emissions pathways, tipping points, etc.). Adjusting the initial parameters to account for these different possibilities yields a set of outcomes to consider in any decision. Even with the broad set of considerations modelled below, the PAGE2002 model does not account for systemic risks resulting from responses to climate impacts outside of parametric variation through the Monte Carlo simulation.

Table 2. Losses in current per-capita consumption from six scenarios of climate change and economic impacts

Scenario		Balanced growth equivalents: % loss in current consumption due to climate change		
Climate	**Economic**	Mean	5th percentile	95th percentile
Baseline climate	Market impacts	2.1	0.3	5.9
	Market impacts + risk of catastrophe	5.0	0.6	12.3
	Market impacts + risk of catastrophe + non-market impacts	10.9	2.2	27.4
High climate	Market impacts	2.5	0.3	7.5

	Market impacts + risk of catastrophe	6.9	0.9	16.5
	Market impacts + risk of catastrophe + non-market impacts	14.4	2.7	32.6

(Stern, 2006)

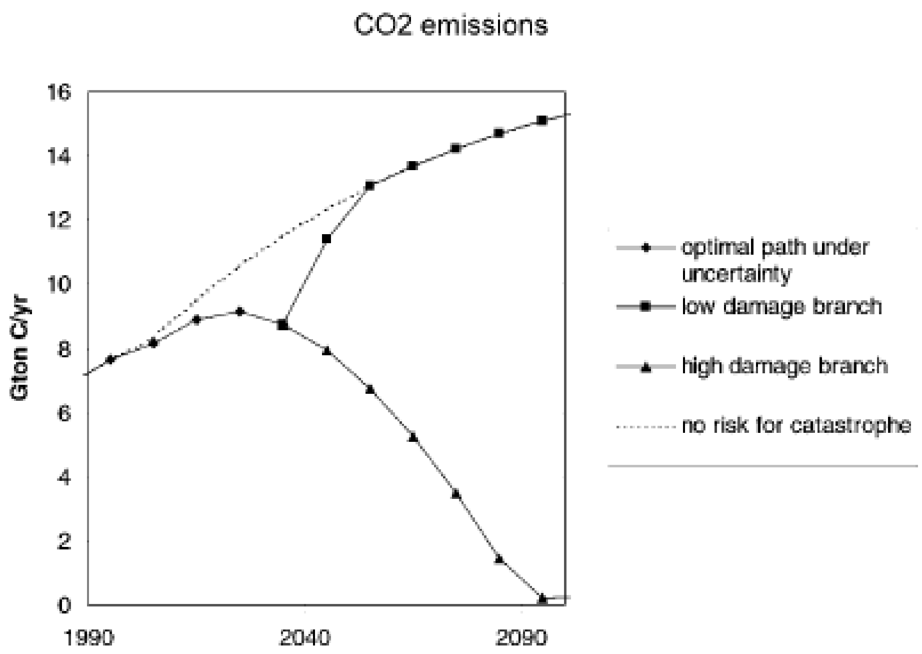
Though these project economic impacts are substantial, analysis by other economists suggests that potential damages from catastrophic climate change may exceed those levels predicted in the Stern Review. Ackerman et. al. (2008) criticise the PAGE2002 IAM used in the Stern Review for underestimating economic damages from climate change. First, the IAM excluded any adaptation costs. Second, the model assumes that catastrophic events such as melting ice sheets are unlikely to occur beneath a 5 degrees Celsius increase in the global average surface temperature. The authors correct this assumption to align with scientific estimates of catastrophic events occurring at 2-4 degrees of warming and at a higher probability than the model includes. The authors also increase the exponent value of the damage function used in the model. These adjustments bring damage estimates in 2100 up from 3.4% GDP to 10.8%, still assuming no-cost adaptation. Subsequent improvements in the updated PAGE09 model include updated parameters for carbon feedback cycles that will produce higher damage estimates than the PAGE2002 (Hope, 2010). These updates and critiques show how economic models are changing to accommodate advancements in understanding of catastrophic risk posed by climate change.

5 Alternative approaches to weighing systemic climate risk

Given the issues with accounting for catastrophic climate change in models and cost benefit analyses, a lack of confidence in existing economic tools is understandable. Amidst the confusion around exact discount rates and costs of climate change, perhaps the wisest route is to steer clear of exactitude. Dietz et al (2007) suggest that economic tools should be used for general guidance in the face of such broad uncertainty. While questions of whether catastrophic climate change will cost 10% or 20% of global GDP in 2200 may not yet be answered with the current tools available, it is enough to recognise that the effects that may come from tipping point events are likely be disruptive and are important to prepare for through alternative planning processes. Some candidates for alternative approaches are discussed below.

Azar and Lindgren (2003) suggest a more dynamic approach to climate modelling whereby estimates are regularly updated with advances in knowledge and understanding of the risks posed to society by any given climate disaster. A dynamic learning approach to climate policy would include future decision points that could be updated as more robust information becomes available (see Figure 5). Analysis of the US SCC estimate recommends regular five-year assessment periods to incorporate the latest learning in climate modelling (Metcalf & Stock, 2015).

Figure 5. Alternative climate policy paths



(Azar and Lindgren, 2003)

Similarly, Lemoine and Traeger (2014) propose a recursive model of climate policy in which policymakers take action as more information on tipping points becomes available to them.

This model assumes that scientists will be able to correct expected impacts of climate change with each instance of temperature increase by observing how resilient the planet is to warming. These corrections may result in a reduction of projected costs of future impacts, allowing for more accurate climate policy tools such as the social cost of carbon or carbon taxes. By running different scenarios through the DICE model, the authors show that optimal carbon-pricing levels should change significantly once more information is available on the resiliency or inadequacy of the Earth's ability to absorb emissions.

5.1 Improving climate models

As discussed above, the use of Integrated Assessment Models in mapping economic value on physical climatic changes is currently central to the state of the art of climate change science. These models allow policymakers to predict the impacts of alternative policy decisions on the environment, the economy and societies around the world, providing valuable information for decisions between different actions, revealing implications for systemic impacts that transcend disciplinary media. The complexity of these models and their span across time and space opens up model results to uncertainty and bias, particularly where parameters such as the discount rate, consumption trends and equity weights are entered exogenously by the modeller. In discussions of using IAMs to set the SCC, economists recognise the necessity of employing integrated models to produce an SCC estimate, but highlight considerations around uncertainty and bias that should be understood in any interpretation of these findings (Metcalf & Stock, 2015).

Discussions of uncertainty in IAMs includes several perspectives on sources of concern and potential paths forward. One analytical treatment points to ambiguity in parameters inputted into IAMs. Values of equilibrium climate sensitivity, details of damage functions, inclusion of the probability of catastrophic events and the discount rate for future costs and benefits are often set by the modeller before an IAM is run. As debate evolves around the appropriate values for each of these parameters, subjectivity in IAMs may be reduced. For systemic risk projections, the inclusion of catastrophic climate events is an important element to consider. Where models do not include these costs, cost estimates such as the SCC may be increased by a supplement to represent expected additional costs from catastrophic climate change. The specification of damage functions also has great bearing on IAM outputs. Rather than pursue a simplified top-down approach which assigns a percentage of GDP loss for a given temperature increase, bottom-up construction informed by damage from extreme short-term weather events can provide a more accurate and informative estimate of costs from physical climatic changes. Regular updates to SCC and other cost models used for government policies can provide opportunity for updates with the latest available scientific agreement on these parameters. An alternative approach is to rely on an expert panel of economists to produce an SCC value, but this is vulnerable to criticisms of political influence and deference to familiar IAMs.

The exclusion of catastrophic costs in most IAMs, combined with insufficient consideration of technological innovation and economic behaviour build a case for pursuing alternative modelling methods. Dietz and Stern (2015) demonstrate how IAMs can be improved to correct for some of the shortfalls outlined in this section, by adjusting the DICE model to account for endogenous growth and catastrophic climate change. The author of the Stern Review recently called for drastic reform to climate modelling practices, encouraging a switch from IAMs to dynamic stochastic computable general equilibrium models or agent-based models (Stern, 2016). Assumptions in IAMs include that of a representative agent—a benevolent social planner implementing the most cost-effective climate policy in an identical fashion across societies (Farmer et al, 2015). In practice, though, empirical evidence demonstrates great heterogeneity in policy decisions, reflecting the importance of social and political context in policy decisions. The representative agent assumption also ignores distributional effects of policies for estimates of macroeconomic impacts. Agent-based models, which explore contextual data around individual decisions, may also provide more useful pictures of behaviour under climate policy. In a report commissioned for the United Kingdom's Department for Environment, economists recommended case studies as a more informative method to consider disparate impacts of climate change across regions of the world, as aggregate macroeconomic modelling does not reveal important details about regional differences in climate impacts (Vivid Economics, 2013).

Other modelling improvements may rely on the implementation of dynamic stochastic computable general equilibrium models, which take a general equilibrium approach to climate modelling but expand input parameters to reflect a range of values, capturing greater uncertainty than the most commonly applied IAMs. This approach requires enormous computing power that may not have been available to early modellers but is possible with modern technology. An application of this method to SCC calculations finds that SCC estimates from DICE and PAGE IAMs are half of optimal levels (Golosov et al, 2014).

5.2 Systemic risk and adaptation

The development of climate models has historically arisen out of conversations around how to stop climate change from a mitigation approach—how many emissions the planet can process, etc. Because of this, today's climate models were designed to produce information useful for mitigation policies. Relying on these same models to inform climate adaptation policy requires a careful approach. Further, adaptation efforts and investments may affect climate outcomes in a way not accounted for in existing modelling tools that prove key in predicting responses to climate shocks. Castells-Quintana et al (2015) suggest that, particularly in poorer countries, *in situ* adaptation efforts may have an added effect of building capacity for transformational adaptation actions in response to systemic risks of human movement and interruptions to food systems, by strengthening institutions and capacity amongst affected populations. The feedback affects in migration and consumption in an affected area may be determined in part by the strength of institutions and resiliency efforts, which most IAMs do not consider.

5.3 Prioritising the worst-off

In light of the difficulties presented by a classical discounted utilitarian approach to calculating the economic values associated with climate impacts, van den Bergh and Botzen suggest a Rawlsian prioritisation of the welfare for the groups most severely impacted by climate change. This 'maximin' approach to climate policy that aims to maximise welfare in a *worst-case* scenario. By considering the worst-off generation, SCC analyses would yield a much higher carbon price. Similarly high SCC values result from applying a 'minimax regret' policy approach that aims to reduce regret from either extreme climate impacts or costly mitigation activities. Van der Ploeg (2014) proposes an additional component in a carbon tax to account for the likelihood of catastrophic climate events increasing non-linearly with global temperature due to positive feedback loops. The use of a precautionary principle to favour more stringent targets can be found in UK climate laws and the recent Paris Agreement.

5.4 Strong sustainability

The use of non-market techniques to value environmental impacts in economic analysis assumes that environmental goods can be expressed in similar terms as goods sold on the market. Through natural capital accounting, economists have made progress in valuing impacts on natural resources and the environment that can prove useful in assessing changes in natural stocks from climate impacts. In the United Kingdom, the work of the Natural Capital Committee has institutionalised national natural capital accounting in order to reduce losses in environmental goods and services that are often left out of traditional GDP wealth conceptions (Helm, 2014). As natural capital may not be replaceable, the "strong sustainability" view holds that converting natural value to monetary units wrongly assumes that natural and manufactured goods are perfectly substitutable (Neumayer, 2013). An alternative that holds natural and market values separate—also piloted in the United Kingdom—is the implementation of multi-criteria decision analysis. This augmentation of traditional cost-benefit analysis assesses the impacts of policy alternatives, but stops short of monetising all costs and benefits—leaving physical changes in project calculations for decision makers to weigh. By listing economic costs next to environmental and social changes resulting from a project, policy makers can compare outcomes across a range of criteria (UK Department for Communities and Local Government, 2009)

Raymond et al (2013) reject even a strong sustainability approach to CBA, pointing to shortfalls in measuring damages to nature by valuing the services produced from a natural system or process. The authors show that common valuation techniques neglect the intrinsic and future values of nature, the value of ecosystem interactions important to the continued provision of natural resources, dynamics of demand and access to services, and other ethical implications. They review alternative views of the human-environment relationship that have implications for how nature is included in economic analysis. Their "web of life" metaphor aims to include ecosystem effects in natural capital valuations. This approach would likely increase the perceived benefits from nature, as well as the cost of damages from climate change and pollution, but requires a much more comprehensive understanding of the dynamics of ecosystems than current practices.

For catastrophic events with great uncertainty, quasi-economic tools proposed in this paper may help inform policy analysis in tandem with, or instead of, traditional cost-benefit analysis. Table 3 summarises criticisms of economic tools for assessing climate risks and reviews alternative tools suggested in the literature that respond to these criticisms. Specified applications of system events stemming from climate impacts will be examined to illustrate potential uses for these tools.

Table 3. Alternatives to existing tools

Issue	Alternative strategies	Literature
Uncertainty over time in climate policy paths	Create decision points along climate policy paths to account for improvements in information and models Create learning system to update tools and information	Azar and Lindgren; Stern
IAMs are constrained in ability to model behaviour, dynamic economic effects and catastrophic climate change	Agent-based models of responsive behaviour Dynamic Stochastic CGE models Case-studies for specific regions	Stern; Vivid Economics
Utilitarian approach in social cost of carbon values	Maximin approach to SCC Minimax regret SCC policy	Van den Bergh and Botzen
Environmental externalities, improper substitution between forms of capital	Natural Capital Accounting, Net National Welfare Approach Social Cost of Carbon	Helm; Tol
Shortfalls of valuing nature in monetary terms	Multi-Criteria Analysis Increased ecosystem feedback information	UK Government; Raymond et al
Absence of systemic risks in model outputs	Rely on outputs as guidance, use narrative analysis to make decisions Supplement SCC estimates with additive catastrophic event cost	Nordhaus; Dietz et al Metcalf & Stock

6 Application: the Syrian Refugee Crisis

One of the most tangible effects of climate change is the forcible displacement of people from home countries as a result of changes in environment, resource scarcity and scarcity-induced conflict. The migration of over 4.7 million Syrians to countries away from their home country to escape a violent civil war since 2011 stands as a present example of migration which has been, in part, attributed to climate variability and change. Thus, Kelley et al (2015) discuss how serious drought in the region from 2007 to 2010 was aggravated by climate change and played a major role in increased political and social instability in Syria. This section will explore the connection between climate change and forced migration and how economic tools are applied to evaluate the costs of migration in climate models and present some alternatives to current practices.

By 2050, over 250 million refugees are projected to be displaced from their homes by the impacts of climate change, a quarter of all displaced persons over this period (Christian Aid, 2007). Though robust data on climate-induced migration is lacking, climate models project physical and social impacts that are likely to lead to significant population shifts. The IPCC expects 1 to 3 billion people to experience water scarcity by 2080, 200 to 600 million to experience hunger and 2 to 7 million to suffer coastal flooding over the same period. The Stern Review projects that in Bangladesh 35 million people will be affected by sea-level rise and in China 300 million will face water scarcity.

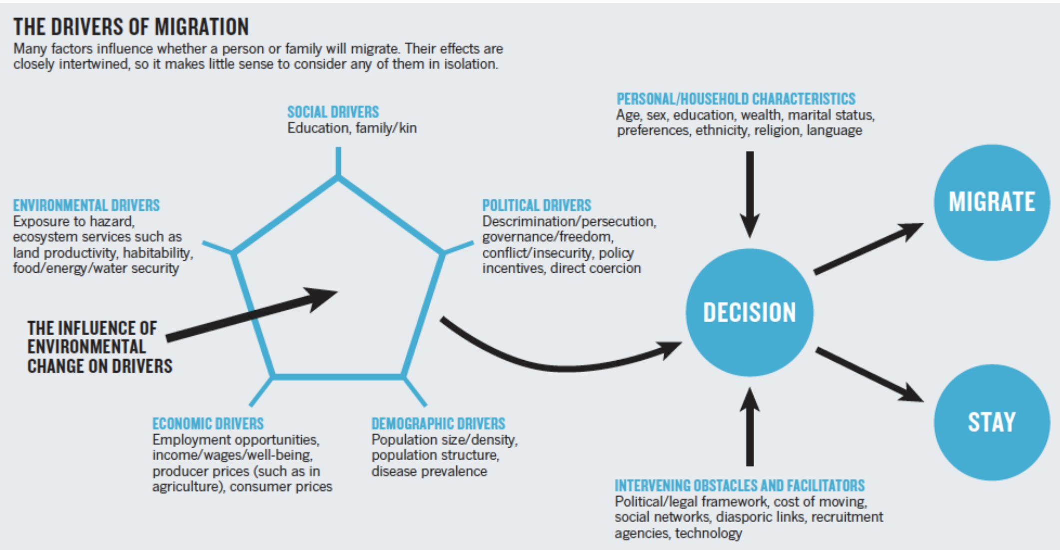
Factors related to climate change that are expected to contribute to increased migration flows include rising rates of conflict stemming from drought, resource scarcity and property damage from sea level rise. Empirical evidence to date shows that conflict occurs frequently in areas of the world where populations are dependent on environmental resources and therefore are highly vulnerable to climate impacts on environmental resources (Raleigh, 2011). For example, the West African Sahel has already experienced drought conditions worsened by human impact that have led to outbreaks in conflict (Nyong et al, 2006). Analysis of “hotspots” resulting from climate-forced environmental degradation predict migration flows from Central America, North and Western Africa, China and the Indian subcontinent (Schubert et al, 2008).

Migration flows may result in second-order and feedback effects in destination countries, which are important to consider when modelling socioeconomic responses to climate change. A UK government study discusses how mounting pressure from incoming migrants may strain social cohesion in destination countries, resulting in tighter control of movement between countries, possibly involving security forces to prevent unauthorised entry (Feakin, 2011). Positive feedback on climate change may result from large migration flows from southern countries to northern countries, which tend to emit more emissions per capita. Thus, in the long-run, an increase in northern populations could lead to increased climate impacts on southern countries, triggering further migration. Policy actions to combat this feedback effect and dissuade south-north migration may include increased expenditure on energy efficiency technology and stricter border control (Marchiori & Schumacher, 2011). In addition, when driven from rural communities by environmental degradation or agricultural disruption, migrants that resettle in coastal urban areas can have the adverse effect of increasing climate risk to themselves and their destination city (Hanson et al, 2011).

6.1 Migration as transformative adaptation

In the context of adaptation to climate change, migrating is a non-trivial option with which affected populations can respond to adverse environmental and social impacts. Migration can be seen as an example of transformative, non-marginal, adaptation. Studies of migration as an adaptation option demonstrate the relationship between environmental change and the decision to leave a country (Black et al, 2011). As shown in figure 6, environmental factors combine with social, political, economic and demographic factors in a given location to inform an individual's decision to remain or migrate. Adger et al (2009) suggest that the societal perception of risk and systematic undervaluation of cultural assets—areas that are not included in many socioeconomic models—may influence adaptation decisions as well. The question of where migrants go to is important, as relocation in vulnerable areas and coastal cities can increase the risk to both the migrant and the destination city by stretching the capacity of existing infrastructure in vulnerable areas. When large-scale migration, such as the abandonment of island nations, is taken into account, political challenges around sovereignty and dislocated government also arise. However, pro-migration policies in developed countries can be argued for on ethical grounds, viewing the intake of migrants as a part of the climate burden wealthier countries have contributed to with historical emissions. Regional economic zones and linked policies between labour market needs and migration flows are examples of policy approaches that can efficiently facilitate climate migration.

Figure 6. Drivers of Migration



(Black et al, 2011)

6.2 Modelling the economics of migration

In modelling changes in welfare from climate-induced migration it is necessary to capture costs to 1) migrants and 2) destination countries. Disentangling climate drivers from other determinants of migration is complex. Our understanding of socioeconomic reactions to climate change on a local level is poorly represented in existing models. This prevents the quantification of risk from migration drivers such as conflict and environmental disaster (Watkiss & Hunt, 2012). In general, data on migration drivers and flows between countries are sparse and modelling techniques lack the complexity to provide a realistic picture of global responses to climate change, reflecting society-specific preferences and behaviour (McLerman, 2013).

Suggested improvements to modelling future climate migration response include the employment of agent-based models (ABMs), which simulate interactions between a large number of actors to predict socioeconomic responses to climate change impacts, including migration patterns (ibid.; Stern, 2016). While current economic models relate migration decisions to GDP, ABMs consider a wider set of factors including individual characteristics and social networks to develop a computer simulation that allows researchers to model outcomes across parameters (Smith et al, 2010). This method can account for heterogeneous preferences and behaviours throughout a population, though it requires a large amount of data specific to a group of people (Piguet, 2010). However, an ABM developed by researchers at the University of Sussex has been able to generate predicted migration behaviour from rainfall changes in Burkina Faso that correlates at a level of 80% with observed behaviour.

Changes in welfare from migration may be large, but are difficult to capture in an aggregate CBA framework. For example, Tol (2002) settles on a value of three times per capita income to represent welfare losses per migrant in the FUND Integrated Assessment Model, but this arbitrary value potentially runs into ethical challenges given differences in income between home and destination countries. For example, the per capita median income in Syria is $1431, whereas the per capita median income in Germany is $14,098, according to a Gallup study from 2006 to 2012 (Phelps & Crabtree, 2013). These differences demonstrate the fact that market prices for labour do not reflect distributional concerns between countries, an element that should be considered when interpreting model findings.

6.3 Alternative approaches to economic modelling of climate migration

In light of problems outlined above with current economic approaches to climate migration policy, alternative tools should be considered for application in this area. First, improvements to modelling can reduce uncertainty and increase the comprehensiveness of economic information included in analysis, addressing some ethical concerns around non-market valuation of livelihoods and social preferences. Second, shared Socioeconomic Pathways provide insight into how macroeconomic systems may develop over the future. Consideration of these alternative development pathways and policy mechanisms designed to perform across these scenarios can result in improvements upon current methods. Finally, explicit and separate treatment of welfare losses amongst climate migrants can lead to more fair and equitable policy decisions in the present. Each of these approaches can be seen as complementary means of accounting for changes in welfare from climate-induced migration.

Strategy 1. Model improvements, as proposed by Stern, Dietz & Hepburn, Smith et al and others, can bring more realistic assumptions into projections of impacts and related costs. Integrated Assessment Models can be run across a number of parametric assumptions in order to include catastrophic climate risks and economic feedback effects from mitigation efforts and climate change impacts, yielding a range of social carbon costs to inform policy costing exercises. National and regional project proposals can be evaluated with specific and dynamic information around future consumption trends in order to yield more representative discount rates over a project's lifetime. Agent-based models can reveal information about migration behaviours in response to climate change. Inputs to models should also be chosen carefully. Non-market values for place-based social and cultural goods are an example of costs not often reflected in climate migration models. Revealed and

Stated Preference-based studies can help to identify appropriate economic values for these goods.

Strategy 2. The IPCC Shared Socioeconomic Pathways present different visions of the future, with variation in challenges facing climate mitigation and adaptation efforts, informed by the level of cooperation between different regions of the world and growth patterns in economies. Climate-induced migration could be expected to be reduced through high-mitigation futures, where impacts of climate change are largely avoided around the world, as well as highly regional scenarios, where barriers to movement are high and migrants have few potential destinations in which to resettle. Consideration of the impacts of a policy decision relevant to climate migration today (mitigation efforts, immigration policies, refugee support infrastructure, etc.) across potential socioeconomic pathways provides a good robustness check for analysis.

Strategy 3. Employing special consideration for the most adversely impacted groups may affect how climate projects and policies are evaluated. In order to maximise the welfare of the most vulnerable regions to climate change impacts in a “maximin” approach, the global and national policy alternatives must be evaluated with separate consideration for how vulnerable regions are affected from any given action. Such an approach can be incorporated into evaluation frameworks with an approach similar to multi-criteria analysis discussed in section 5.3, with which CBA evaluations can state impacts on migration flows within and addition to economic costs. Cross-cutting project measures that protect vulnerable populations can also be an application of this principle, such as an emergency fund for climate migrants or migration infrastructure investments that proceed a particular migration-inducing event.

These strategies can be applied individually or in combination to current evaluation methods to account for systemic risk posed by climate migration patterns.

6.4 A climate risk management view of the Syrian refugee crisis

As of February 2016, over 4.72 million Syrians were displaced from their home country, claiming refuge in friendly countries around the world (UNHCR & Government of Turkey, 2016). These refugees can be seen to be amongst the first massive climate migration flows, escaping political instability and civil war for which an extreme drought served as a contributing factor (Kelley et al, 2015). Coverage of the refugee crisis has centred on the unpreparedness of the international community for receiving these migrants. An examination of the costs incurred by the global community and reactions to migrant flows can prove educational for assessing the suitability of current economic tools.

The United National High Commission on Refugees estimates over $4.5 billion in aid is needed to accommodate refugees from Syria, covering resettlement costs and social services to refugees once placed in host communities. The annual cost of hosting refugees varies across countries, due primarily to differences in costs of living, ranging from $1000-2000 per refugee in countries bordering the war-torn country to over $12,000 in the US and some European countries. These costs include administrative fees, social welfare support for relocated refugees and public services such as education, housing and healthcare. Table 5 breaks down these costs for a single refugee in the case of the United States. Not included in these cost estimates are a number of non-market costs of migration including costs on both migrant populations and destination country populations. Amongst migrants, significant costs may be associated with loss of community, culture and a sense of security, all of which are not completely captured by existing measures. Destination countries may face significant costs related to social angst or fear of incoming migrant populations, seen starkly in political rhetoric and government responses to migration in the Syrian crisis. First-line government vetting costs are included in the application fees identified in Table 5, but expanded surveillance programmes, reinforced borders and losses in tourism income are not captured in a systematic evaluation (anecdotal estimates are included in Table 6). Even if these official expenditures are included in cost estimates, they may not match the social non-market preferences on migration that destination country populations retain.

Table 5. U.S. refugee resettlement costs over a 5-year period (per migrant)

External application/arrival costs	$4,433
Internal arrival/relocation costs	$4797
Welfare and food expenditures[1]	$14,892
Education and healthcare expenditures	$40,249
Total quantified costs	**$64,317**
Annual Total	$12863

[1]The U.S. Office of Refugee Resettlement reports that most refugees become economically self-sufficient within five years of relocating. Cash benefits taper over this period as individuals approach the income threshold for welfare benefits.

Source: (Camarota & Zeigler, 2015)

Along with neighbouring Turkey, Lebanon and Jordan, Europe has become a major destination for those seeking relief. Over 2.5 million migrants have applied for relocation within the European Union. Current and planned levels of migration are high enough that host countries are estimating costs for refugees in proportions of GDP. The economic impacts of migration to host countries range from 0.1% to a few percentage points of GDP, with larger effects experienced by smaller economies. Across Europe, host countries project spending between 0.1 and 0.9% of GDP on refugee populations. Over the long term, migration is anticipated to benefit countries by bolstering their labour force, but high resettlement and social welfare costs when migrants first arrive represent large and often unplanned expenses on behalf of destination countries that can reduce adaptive capacity throughout socioeconomic systems. Nearly a full percent of annual GDP does represent significant resources, however, and limited evidence shows short-term impacts of lower wages, stretched social services and limited tax contributions in areas with high resettled refugee populations. Table 5 presents available data on the resettlement of refugees to date, including both up-front costs and indirect economic effects from large refugee populations. These figures are based on available information at the time of writing. A comprehensive comparison of costs and migration flows is not possible due to changing circumstances of the ongoing crisis.

Table 6. Syrian refugee crisis costs

Host country	Number of refugees	Estimated annual quantitative costs	Cost per refugee	Indirect costs
Lebanon	1.2 million	$800 million in aid		23% decrease in tourism, 7.5% decrease in exports
Jordan	0.8 million	$1.6 billion; 2.4% GDP in 2014	$2000	Fixed infrastructure upgrade cost of $1.2 billion
Iraq	245,022			
Egypt & North Africa	117,658			
USA	10,000	$128 million	$12,874 for first five years	
Turkey	2.5 million	$4.5 billion over 4 years		Stagnant wages, unemployment, inflation in resettled areas; hospital capacity overtaken by refugee needs
Germany	0.83 million	€10 billion, 0.5% GDP through 2017	€12,000	
Sweden		0.9% GDP in 2016		
Austria		0.1-0.3% GDP from 2014-2016		
Hungary		0.1% GDP in 2015		
Global	4.72 million	$4.2 billion[1] requested by		

[1] Total funding requirements identified in UNHCR Regional Refugee & Resilience Plan 2015-2016

Total		UNHCR; European countries have spent or pledged €8 billion[2] on relief efforts		

(UNHCR & UNDP, 2015); (Nasser & Symansky, 2014); (Camarota & Zeigler, 2015);

(Orhan & Gündoğar, 2015); (OECD, 2015)

A short exercise to consider alternative approaches to the current crisis considers implications of planning for migration flows using tools discussed in the previous section. The current refugee crisis caught much of the world off-guard with the magnitude of refugees leaving their homes, with European leaders in particular deferring to Syria's neighbouring countries to absorb 98% of migrants through 2014 before developing a relief plan (Orchard & Miller, 2014). Systematic funding for refugees was not organised at an international level until a 2016 London conference (UNHCR, 2016). As such, responses to migration have been ad hoc and lacking central coordination, except for logistical support for aid workers coordinated through the United Nations. Alternate economic planning tools may have resulted in an improved response at less cost to host countries, migrants and international economic systems. Consideration of these approaches may provide guidance for use in managing future migration crises.

Applying the first strategy discussed in section 6.3 would require the use of many already available tools to anticipate the costs of climate change. Climate IAMs have been used to generate estimates for the social cost of carbon that can capture impacts from climate change and factor the costs of these impacts into policy and project decisions. State of the art IAMs, though, do not include robust models of human behaviour on par with agent-based models. Also, SCC estimates are of limited use for impacts involving international flows such as climate migration. Assumptions about future consumption also have important implications for discount rates used in infrastructure project evaluations. Finally, valuing welfare changes to migrants from other countries entering destination countries raises the question of how to value welfare across different income categories. Planning exercises such as the United Kingdom's Foresight Report on Migration and Global Environmental Change (2011) can incorporate these methods to anticipate the arrival of climate refugees and mobilise resources to support their asylum. This study identified the importance of environmentally-induced migration, but failed to connect these warnings to the ongoing crisis in Syria at the time of the report's publication. Governments anticipating large numbers of climate migrants might have put in place infrastructure to distribute refugees in an efficient and fair manner across countries prepared to receive them. Robust economic models cannot predict the future, but could go a long way towards helping governments prepare for potential crises.

Using socioeconomic scenarios to plan climate policy can incorporate broad uncertainty into policy decisions, offering analytical perspective from various future development pathways. These growth pathways have particular salience for long-term climate policy. Systems and rules created to manage the Syrian refugee crisis can provide an important precedent to rely

[2] European Commission Syria crisis factsheet, http://ec.europa.eu/echo/files/aid/countries/factsheets/syria_en.pdf

on in future migration events. By developing principles for distributing refugees, for example, host countries can implement policies for managing climate migration across SSPs. EU, OECD and Arab League commitments to distribute climate migrants can provide certainty and guidance for future crises despite the integration or economic development levels predicted in different scenarios. With reference to the SSPs, policymakers can design resettlement programmes to prevent the debates and delays currently present in the Syrian crisis. Plans and programmes put in place today should be evaluated for their resilience in regionally fragmented and globally integrated futures, as well as high and low economic development scenarios.

A policy approach that offers unique categorical consideration of impacts on the most vulnerable populations has specific relevance for those forced into migration by climate impacts. Applying a maximin ethic to climate policy requires acting to maximise the welfare of the worst-impacted from any policy choice. In the case of climate refugees, any policy option that reduced emissions, increased local resilience to climate impacts and—in the event of a need for migration—resettled migrants with the greatest ease and speed to displaced persons would all be preferred by this ethic. Specific to this event, a lack of organised funding and resettlement plans has left millions of Syrian refugees without a safe refuge. An emergency fund for future climate migration effects can provide resources to aid refugees driven out of their homes by a particular climate event, and blunt the costs of a response to host countries. As shown in Table 5, European and Arabic countries are devoting incredible resources, up to 2.4% of national GDP, to respond to the refugee crisis. An international fund built up over time would provide less of a shock to these countries than an immediate call for large amounts of resources, as was agreed at the London aid conference in early 2016, where $9 billion in aid was pledged for the Syrian refugee crisis from developed countries.

These critiques are in part philosophical and may be more useful for future refugee crises than for the current event. Improving models and valuation methods, planning for outcomes across socioeconomic scenarios and considering the welfare of the most adversely impacted by climate change are all constructive approaches to improving the use of economics in climate policy. In a simulation exercise among senior military leaders from around the world, half of the teams decided to invest in climate geoengineering technologies—a policy option seen to carry great risk—when presented with potential migration flows stemming from climate change (King et al, 2015). This serves as evidence of the high-stakes challenges facing climate policymakers and the urgency for developing tools and methods to aid in the management of systemic risks.

7 Conclusions

This paper explores the nature of systemic risks from climate change from the perspective of economic tools available to policy makers in making decisions between alternatives. Modern tools, especially integrated models and scenarios based on socioeconomic pathways, are explored with consideration of criticisms related to ethical assumptions included in these models, accuracy of model outputs, omissions of catastrophic climate impacts and shortfalls in model application. Alternatives to current practice are reviewed, including updates to the implementation of existing models, broader interpretation of model outputs, special consideration of vulnerable populations and the use of entirely different models to estimate economy-wide and socially contingent behaviour. An illustrative application of these alternative approaches shows how climate migration can be approached in planning exercises and policy choices.

Useful lessons across model types include testing assumptions over different socioeconomic and emission pathways, updating models with current information at regular intervals and limiting model outputs to guide, rather than decide policy action.

8 References

Ackerman, F., E.A. Stanton, C. Hope and S. Alberth. 2008. Did the Stern Review underestimate U.S. and global climate damages? Stockholm Environment Institute Working Paper WP-US-0802.

Adger, W.N., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D.R. Nelson, L.O. Naess, J. Wolf and A. Wreford. 2009. Are there social limits to adaptation to climate change? *Climatic Change*, 93: 335-354.

Anthoff, D., R.S.J. Tol and G.W. Yohe. 2008. Risk aversion, time preference and the social cost of carbon. ESRI Working Paper No. 252. Economic and Social Research Institute, Dublin, Ireland.

Atkinson, G. and S. Mourato. 2008. Environmental cost-benefit analysis. *Annual Review of Environment and Resources*, 33: 317-344.

Azar, C. and K. Lindgren. 2003. Catastrophic events and stochastic cost-benefit analysis of climate change. *Climate Change*, 56: 245-255.

Beckerman, W. and C. Hepburn. 2007. Ethics of the discount rate in the Stern Review on the Economics of Climate Change. *World Economics*, 8: 1: 187-210.

Bennett, J. and J. Blamey. 2001. *The Choice Modelling Approach to Environmental Valuation.* Edward Elgar: Cheltenham.

Black, R., Bennett, S. R. G., Thomas, S. M. and J. R. Beddington (2011) Migration as Adaptation. *Nature*, 478: 447-449.

Bolt K., Ruta G. and Sarraf M. 2005. Estimating the cost of environmental degradation: A training manual in English, French and Arabic. *Environment Development Papers*. The World Bank: Washington DC.

Bosello, F., R. Roson and R. S. J. Tol. 2005. Economy-wide estimates of the implications of climate change: human health. Working paper, Fondazione Eni Enrico Mattei, No. 97.

Brysse, K, N. Oreskes, J. O'Reilly and M. Oppenheimer. 2013. Climate change prediction: erring on the side of least drama. *Global Environmental Change*, 23: 327-337.

Camarota, S.A. and K. Zeigler. 2015. The high cost of resettling Middle Eastern refugees. Center for Immigrations Studies, Washington, D.C.

Carter, T.R., R.N. Jones, X. Lu, S. Bhadwal, C. Conde, L.O. Mearns, B.C. O'Neill, M.D.A. Rounsevell and M.B. Zurek. 2007. New Assessment Methods and the Characterisation of Future Conditions. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 133-171.

Castells-Quintana, D., M.d.P. Lopez-Uribe and T. McDermott. 2015. Climate change and the geographical and institutional drivers of economic development. Centre for Climate Change Economics and Policy Working Paper No. 223. London School of Economics and Political Science.

Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann. 2014. Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 945-977.

Christian Aid. 2007. Human tide: The real migration crisis. London.

Dietz, S. and C. Hepburn. 2013. Benefit-cost analysis of non-marginal climate and energy projects. *Energy Economics*, 40: 61-71.

Dietz, S., C. Hope and N. Patmore. 2007. Some economics of ‘dangerous’ climate change: reflections on the Stern Review. *Global Environmental Change.* 17: 3-4: 311-325.

Dietz, S. and N. Stern. 2015. Endogenous growth, convexity of damage and climate risk: how Nordhaus’ framework supports deep cuts in carbon emissions. *The Economic Journal*, 125: March: 574-620.

European Systemic Risk Board. 2016. Reports of the Advisory Scientific Committee: too little, too sudden: transition to a low-carbon economy and systemic risk. ASC Report No. 6.

Falloon, P., A. Challinor, S. Dessai, L. Haong, J. Johnson and A.-K. Koehler. 2014. Ensembles and uncertainty in climate change impacts. *Frontiers in Environmental Science*, 2: 33: 1-7.

Farmer, J.D., C. Hepbrun, P. Mealy and A. Teytelboym. 2015. A third wave in the economics of climate change. *Environment and Resource Economics*, 62, 329-357.

Feakin, T. 2011. International Dimensions of Climate Change Discussion paper 6: The Ramifications of Climate Change – the security perspective. Foresight Project. BIS. London.

Geldhill, R., D. Hamza-Goodacre, L.P. Low and H. Graham. 2013. International threats and opportunities of climate change for the UK. Pwc report for UK Department of Environment, Food and Rural Affairs, London.

Gollier, C., P. Koundouri, T. Pantelidis, J. Boone and P. Geoffard. 2008. Declining discount rates: implications for long-run policy [with discussion]. *Economic Policy*. 23: 56: 757-795.

Guillerminet, M.-L. and R.S.J. Tol. 2008. Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet. *Climatic Change*, 91: 193-209.

Golosov, M., J. Hassler, P. Krusell and A. Tsyvinski. 2014. Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82: 1: 41-88.

Hallegatte, S., Hourcade, J.C., Dumas, P., 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecological Economics 62 (2), 330–340

Hanson, S., R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer and J. Chateau. 2011. A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, 104:89–111.

Helm, D. 2014. Taking natural capital seriously. *Oxford Review of Economic Policy*. 30: 1: 109-125.

Hope, C. 2010. The PAGE09 model: estimating climate impacts and the social cost of CO2. U.S. Environmental Protection Agency. Washington.

Hultman, N. E., D. M. Hassenzahl and S. Rayner. 2010. Climate risk. *Annual Review of Environmental Resources.* 35: 283-303.

International Institute for Applied Systems Analysis. 2015. Model Description. SSP Database. https://tntcat.iiasa.ac.at/SspDb/download/iam_scenario_doc/SSP_Model_Documentation.pdf . Accessed: 23 February 2016.

Kelley, C.P., S. Mohtadi, M.A. Cane, R. Seager and Y. Kushnir. 2015. Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academies of Science*, 112: 11: 3241-3246.

King, D., D. Schrag, Z. Dadi, Q. Ye and A. Ghosh. 2015. Climate change: a risk assessment. UK Foreign and Commonwealth Office, China National Expert Committee on Climate Change, Skoll Global Threats Fund, UK Institute and Faculty of Actuaries and Willis Group Holdings. London.

Kunz, M., B. Mühr, T. Kunz-Plapp, J.E. Daniell, B. Khazai, F. Wenzel, M. Vannieuwenhuyse, T. Comes, F. Elmer, K. Schröter, J. Fohringer, T. Münzberg, C. Lucas and J. Zschau. 2013. Investigation of superstorm Sandy 2012 in a multi-disciplinary approach. *Natural Hazards and Earth System Sciences*. 13: 2579-2598.

Layard, R., G. Mayaz and S. Dickell. 2007. The marginal utility of income. Centre for Economic Performance Discussion Paper No. 784. London School of Economics and Political Science.

Lemoine, D. and C. Traeger. 2014. Watch your step: optimal policy in a tipping climate. *American Economic Journal: Economic Policy*. 6: 1: 137-166.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf and H.J. Schellnhuber. 2008. Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, 105: 6: 1786-1793.

Mankiw, N.G. 2000. *Principles of Microeconomics*. South-Western College Publications, 2nd Edition.

Marchiori, L. and I. Schumacher. 2011. When nature rebels: international migration, climate change, and inequality. *Journal of Population Economics*, 24: 2: 569-600.

McLerman, R. 2013. Developments in modelling of climate change-related migration. *Climatic Change*, 117: 599-611.

Mechler, M., L.M. Bouwer, J. Linnerooth-Bayer, S. Hochrainer-Stigler, J.C.J.H. Aerts, S. Surminski and K. Williges. 2014. Managing unnatural disaster risk from climate extremes. *Nature Climate Change*, 4: 235-237.

Metcalf, G. and J. Stock. 2015. The role of integrated assessment models in climate policy: a user's guide and assessment. Discussion Paper 15-68. The Harvard Project on Climate Agreements, Harvard Kennedy School, Cambridge.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis.* Island Press, Washington, D.C.

Nasser, R. and S. Symansky. 2014. The fiscal impact of the Syrian refugee crisis on Jordan. Fiscal Reform II Project, United States Agency for International Development, Amman.

Neumayer, E. 2013. *Weak versus strong sustainability: exploring the limits of two opposing paradigms*, Edward Elgar: Cheltenham, 4th edition.

Nordhaus, W. D. 2011. The economics of tail events with an application to climate change. *Review of Environmental Economics and Policy*. 5: 2: 240-257.

Nyong, A., C. Fiki and R. McLerman. 2006. Drought-related conflicts, management and resolution in the West African Sahel: considerations for climate change research. *Die Erde*, 137: 3: 223-248.

O'Brien, K. 2012, Global environmental change II: from adaptation to deliberate transformation. *Progress in Human Geography*, 36: 5: 667-676.

O'Neill, B.C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B.J. van Ruikven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy and W. Solecki. 2015. The roads ahead: narratives for shared socioeconomic pathways describing futures in 21st century. *Global Environmental Change*.

O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur and D.P. van Vuuren. 2013. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122: 387-400.

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi. 2014. Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

Orchard, C. and A. Miller. 2014. Protection in Europe for refugees from Syria. Forced Migration Policy Note, Refugee Studies Centre, University of Oxford.

Organisation for Economic Cooperation and Development. 2015. How will the refugee surge affect the European economy? *Migration Policy Debates*, 8: November.

Orhan, O. and S.S. Gündoğar. 2015. Effects of the Syrian refugees on Turkey. ORSAM Report No. 195. Center for Middle Eastern Strategic Studies, Ankara.

Parry, M.L., O.F. Canziani, J.P. Palutikof and Co-authors. 2007. Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, (eds.)], Cambridge University Press, Cambridge, UK, 23-78.

Perman, R., Y. Ma, J. McGilvray and M. Common. 2003. "Valuing the environment". In *Natural Resource and Environmental Economics* [R. Perman, Y. Ma, J. McGilvray and M. Common (eds.)]. Pearson Education Limited, Essex, 3rd edition.

Phelps, G. and S. Crabtree. 2013. "Worldwide, median income about $10,000." *Gallup Daily*, http://www.gallup.com/poll/166211/worldwide-median-household-income-000.aspx. Accessed: 25 February 2016.

Piguet, E. 2010. Linking climate change, environmental degradation, and migration: a methodological overview. *Climate Change* (Wiley Interdisciplinary Reviews), 1: 4: 517-524

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor. 2007. Climate Models and Their Evaluation. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Raleigh, C. 2011. The search for safety: the effects of conflict, poverty and ecological influences on migration in the developing world. *Global Environmental Change*, 21S: S82-S93.

Raymond, C.M., G.G. Singh, K. Benessaiah, J.R. Bernhardt, J. Levine, H. Nelson, N.J. Turner, B. Norton, J. Tam and K.M.A. Chan. 2013. Ecosystem services and beyond: using multiple metaphors to understand human-environment relationships. *BioScience*, 63: 7: 536-546.

Schubert, R., Schellnhuber, H.J., Buchmann, Epiney, A., Griesshammer, R., Kulessa, M., Messner, D., Rahmstorf and J. Schmid. 2008. Climate Change as a Security Risk. Earthscan, London.

Smith, C., S. Wood and D. Kniveton. 2010. Agent-based modelling of migration decision-making. Paper presented at 8th European Workshop on Multi-Agent Systems, Paris.

Stern, N. 2006. The Stern Review. UK Cabinet Office. London.

Stern, N. 2016. Current climate models are grossly misleading. *Nature*, 530: February 25: 407-409.

Tol, R.S.J. 2002. Estimate of the damage costs of climate change *Environmental and Resource Economics*, 21: 47-73.

Tol, R.S.J. 2015. Economic impacts of climate change. University of Sussex Economics Working Paper Series. No. 75-2015.

United Kingdom Department of Communities and Local Government. 2009. Multi-criteria analysis: a manual. London.

United Kingdom Government Office for Science. 2011. Foresight: migration and global environmental change. London.

United Nations High Commission on Refugees. 2016. London Syria conference: world leaders urged to help Syrian. News Stories, UNHCR. http://www.unhcr.org/56b1fc4f6.html. Accessed: 1 March 2016.

United Nations High Commission on Refugees and United Nations Development Program. 2015. Impact of humanitarian aid on the Lebanese economy. United Nations.

United Nations High Commission on Refugees and the Government of Turkey. 2016. Syria Regional Refugee Response: Inter-agency Information Sharing Portal. http://data.unhcr.org/syrianrefugees/regional.php. Accessed: 23 February 2016.

Van den Bergh, J.C.J.M. and W.J.W. Botzen. 2015. Monetary valuation of the social cost of CO2 emissions: a critical survey. *Ecological Economics.* 114: 33-46.

Van der Ploeg, F. 2015. Abrupt positive feedback and the social cost of carbon. *European Economic Review*. 67: 28-41.

Vivid Economics. 2013. The macroeconomics of climate change. Report prepared for the UK Department of Environment, Food and Rural Affairs. London.

Watkiss, P., D. Anthoff, T. Downing, C. Hepburn, C. Hope, A. Hunt and R. Tol. 2005. The Social Costs of Carbon Review: Methodological Approaches for Using SCC Estimates in Policy Assessment. UK Department of Environment, Food and Rural Affairs. London.

Watkiss, P. and A. Hunt. 2012. Scoping study: reviewing the coverage of economic impacts in the CCRA. Report to the Committee on Climate Change Adaptation Sub-Committee. Paul Watkiss Associates, London.

Weitzman, M. L. 2001. Gamma discounting. *American Economic Review*, 91: 1: 260-271.

Weitzman, M.L. 2009. On modelling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, 91: 1: 1-19.

Weitzman, M. L. 2011. Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy.* 5: 2: 275-292.

World Bank Group. 2015. State and trends of carbon pricing 2015. World Bank and Ecofys report. Washington, D.