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Abstract

This article reviews the economic and analytical challenges of adaptation to climate change. Adaptation to climate risks that can no longer be avoided is an important aspect of the global response to climate change. Humans have always adapted to changing climatic conditions, and there is growing, if still patchy, evidence of widespread adaptation behaviour. However, adaptation is not "autonomous", as sometimes claimed. It requires knowledge, planning, coordination and foresight. There are important adaptation gaps, behavioural barriers and market failures, which hold back effective adaptation and require policy intervention. We identify the most urgent adaptation priorities, areas where delay might lock in future vulnerability, and outline the decision-making challenges of adapting to an unknown future climate. We also highlight the strong inter-linkages between adaptation and economic development, pointing out that decisions on industrial strategy, urban planning and infrastructure investment all have strong bearing on future vulnerability to climate change. We review the implications of these links for adaptation finance, and what the literature tells us about the balance between adaptation and mitigation.

Keywords: climate change adaptation; climate-resilient development; climate change policy; natural disasters

JEL codes: O29, Q54, Q56

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1. Introduction

The Paris Agreement on climate change, adopted in December 2015, calls for action on both the causes and consequences of climate change. The *causes* of climate change are to be addressed through a drastic reduction in greenhouse gas emissions (mitigation), its *consequences* through an equal emphasis on investment in climate resilience (adaptation). The distinction between mitigation and adaptation is as old as the debate on climate policy itself (see e.g., Watson et al. 1995). However, the attention of policy makers and (to a lesser extent) the economics profession has always been more on mitigation. This paper synthesises the state of knowledge on the economics of adaptation to climate change.

The nomenclature around adaptation can be confusing and is worth clarifying upfront. Related disciplines, in particular the risk management literature, often use the term mitigation (rather than adaptation) to describe actions that reduce climatic risks. In the development literature it has become common to talk about climate-resilient development, rather than adaptation, to emphasise the strong links between adaptation and economic development (see section 4).

The Intergovernmental Panel on Climate Change (IPCC) defines resilience as the ability of a system to anticipate, absorb, accommodate or recover from a hazardous event (Field et al 2012). In contrast, adaptation is the process of adjustment to climate effects, in order to moderate the negative and/or enhance the positive impacts of climate change. Despite these subtle differences, the terms adaptation and climate resilience are often used interchangeably. Other terms that are used frequently, and often loosely, are vulnerability (the propensity or predisposition to be adversely affected) and exposure (the presence of people and environmental, economic, social or cultural assets in places that could be adversely affected).

There is a strong connection and much cross-fertilisation between economic studies of adaptation and the much larger literature on the economic impacts of climate change (surveyed by Dell et al. 2014 and Carleton and Hsiang 2016). This paper is only concerned with the former. However, a clear delineation is not always possible. Indeed, the objective of many, particularly earlier, adaptation studies has often been to refine our understanding of climate change impacts. It was recognised that "farmers were not dumb", as it was put at the time (Schneider et al. 2000), and an accurate impact assessment had to factor in people's response to the new climate conditions.

However, adaptation research has now become an area of academic interest in its own right. The fifth assessment report of the IPCC devoted an entire chapter to the economics of adaptation, which includes over 500 references (Chambwera et al. 2014).

Other surveys of adaptation economics include Markandya et al (2014), Kahn (2016) and Massetti and Mendelsohn (2015). Particularly the last two emphasise the power of adaptation as an autonomous reaction by private actors. Yet adaptation cannot be taken for granted. What may appear autonomous from a distance is in fact the result of deliberate choices by economic agents (farmers, city planners, households) in response to particular information sets, market incentives and policy signals. The decisions they take are often complex and worth studying more closely.

This paper explores the decisions which economic agents, both public and private, face in trying to respond to climate risks. It confirms that adaptation can indeed be very effective at reducing climate risks, but it also highlights the difficulties of effective adaptation, the need for an economy-wide approach to climate resilience and the importance of public policy in facilitating sound adaptation behaviour.

The structure of the paper is as follows. Section 2 discusses the main analytical tools which have been deployed in adaptation economics, including integrated assessment models, econometric models, economy-wide models and various decision making tools. Section 3 discusses adaptation from a microeconomic perspective. The section highlights the prevalence of private adaptation in many contexts, but also identifies potential barriers to adaptation and therefore a role for public policy. The section also makes normative recommendations on initial adaptation priorities. Section 4 adopts a more aggregate, or macroeconomic, perspective. It discusses the links between adaptation, economic growth and development; adaptation finance and costs, and the interplay between adaptation and mitigation. Section 5 concludes.

2. The analytical tools of adaptation economics

There are many analytical angles to adaptation. There is both theoretical and empirical analysis. Some questions are positive, many more are normative. There are microeconomic questions and more macroeconomic issues. Within this diversity, some economic methods have proven to be more useful than others. Important insights have been gained in particular from four main tools: integrated assessment models, empirical (econometric) analysis, economy-wide simulation models and decision support tools. Each of these approaches can help to shed light on different aspects of the adaptation problem (see Fisher-Vanden et al. 2013 for a survey).

2.1 Integrated assessment models

Integrated assessment models seek to represent in full the economic and biophysical processes associated with climate change, from economic activity to emissions, atmospheric concentration, temperature change, physical impacts and socio-economic consequences. The models therefore have to be global, dynamic and long-term, with time horizons of 100 years or more. They have to simulate not just the climate, but also how the global economy will evolve over time as a consequence of population dynamics, capital accumulation and technical progress. This necessarily requires simplification, but also a careful treatment of the inherent uncertainties.

The first integrated assessment models began to emerge in the mid-1990s (Weyant et al. 1995). Adaptation only featured indirectly in this first generation of models. The costs and benefits of adaptation were incorporated in the damage function, that is, in the stylized representation of climate change impacts. Conceptually, the damage function, *D(T),* was defined as the least-cost combination of adaptation costs, AC, and residual damages, *RD*. That is,

$$D(T) = argmin_A\,(AC(A,T) + RD(A,T)) \qquad (1)$$

where *A* is the adaptation effort and *T* is global mean temperature.

In reality equation (1) was not explicitly modelled and the optimality of the adaptation process was merely assumed. The damage functions simply combined estimates of adaptation costs (in particular those related to coastal protection and changes in energy demand) with estimates of residual damages (for example, changes in agricultural yields). However, the optimality assumption allowed modellers to ignore adaptation decisions and focus on other issues of interest, such as the optimal emission reduction path or the social cost of carbon.

Many prominent integrated assessment models, such as the widely used DICE model, are still based on this structure (see Nordhaus and Sztorc 2013). However, there have also been attempts to separate out adaptation and create “adaptation integrated assessment models”, which jointly optimise adaptation and mitigation action across mitigation costs, adaptation costs and residual damage. Most of them are spin-offs of existing integrated models, including DICE/RICE (de Bruin et al. 2009; de Bruin 2011; de Bruin and Dellink 2011) and WITCH (Bosello et al. 2010). Agrawala et al (2011a) use both these platforms.

The simplifications needed to make integrated assessment models tractable and the difficulties in calibrating credible damage functions have been severely criticised, most prominently by Pindyck (2013) and Stern (2013, 2016) who have both questioned the value of such models. Much of that criticism is justified. However, it does not invalidate integrated assessment as an analytical approach. Integrated assessment models are well suited to study important questions such as the interplay between adaptation and mitigation (see section 4.3) and the dynamic ramp up of adaptation over time (see section 3.4). What their structural shortcomings imply is that the models should only be used to study key relationships, trends and sensitivities and not to produce firm numerical estimates.

2.2 Econometric analysis

An important task of adaptation economics is to understand and document how economic agents respond to current climate and weather events. Much of this evidence is provided through detailed, often interdisciplinary case studies (e.g, Penning-Rowsell et al 2013 on migration; Ranger and Surminski 2013 on the demand for insurance). However, increasingly researchers use large household, firm or farm-level datasets to explore how swiftly, comprehensively and rationally economic agents adapt. The evidence is particularly rich for the agriculture sector.

The methodological challenges of such "climate econometrics" have been reviewed by Dell et al (2014) and Hsiang (2016). Both survey papers are concerned primarily with impact assessment and the effect of climatic factors on economic variables like labour productivity, output and growth, rather than the benefits, costs or extent of adaptation. However, many of the insights of Hsiang and Dell et al also apply to adaptation econometrics.

Researchers have sought to identify climate effects both cross-sectionally, by comparing impacts and/or adaptation behaviour across different climate regimes, and inter-temporally, by measuring the impact of particular weather events, such as floods, over time. Increasingly, they have access to panel data.

Cross-sectional studies are closely associated with the "Ricardian approach" pioneered by Robert Mendelsohn (e.g. Mendelsohn et al 1994, Kurukulasuriya et al. 2011, Seo and Mendelsohn 2008 and Wang et al. 2010). Given the wide diversity of climates around the globe, these studies offer ample evidence of adaptation behaviour. However, a disadvantage of cross-sectional studies is that econometricians only observe the long-term steady state under different climate regimes, and not the adjustments that agents go through as they move from one state to the other. The "dumb farmers" of early impact assessments (Schneider 2000) are replaced by agents who are capable of instantaneous, frictionless adaptation. The studies therefore offer little information about the actual costs and benefits of adaptation. There is also the analytical challenge of separating climate effects from confounding factors like culture, history and institutions, which also vary across space (and may sometimes be endogenous).

A key advantage of time series analysis is that weather variations are clearly exogenous and spatial factors like institutions are kept constant. Identification is therefore much easier. Their drawback is that the observable fluctuations tend to be short-term, and the results are therefore more likely to describe the impact of weather variations rather than long-term climatic factors. The models are more likely to identify short-term responses rather than long-term adaptation.

Panel data can overcome some of these short-comings. For example, by interacting weather fluctuations with average climate conditions it is possible to isolate the effect of long-term adaptation on short-term shocks (Hsiang and Narita 2012; Deschêne and Greenstone 2011). Studying weather trends over longer periods (say decadal weather averages rather than short-term shocks) can similarly help to identify long-term adaptation effects (Burke and Emerick 2016).

We will use the insights of empirical models in particular when discussing private adaptation in section 3.1.

2.3 Economy-wide simulation models

Climate change is a planetary issue that affects all countries and most sectors. It is important therefore to understand the economy-wide aspects not just of climate change but also of climate change adaptation. The way in which an economy adjusts to climatic shocks (for example through changes in relative prices) has been described as an important form of adaptation in its own right (Fisher-Vanden et al. 2013).

Through the supply chain, climate vulnerability in one sector, such as agriculture, will spill over into others, such as food processing and textiles (Mideksa 2010). Similarly, the adaptation measures taken in one sector may have repercussions for other sectors. Flood-prone farmers may move to urban areas, depressing wages in cities and the price of land in the rural areas they leave behind. Other economic agents will respond by reducing their labour supply and/or taking advantage of lower land prices, until the economy is again in equilibrium (Banerjee 2007).

While economy-wide effects are captured implicitly in econometric studies (see section 2.2 above) analysing them explicitly means applying system-wide models – computable general equilibrium models, macroeconomic models and input / output analysis. Researchers also turn to system-wide models to obtain, within a consistent framework, an estimate of the combined effects of adaptation to multiple climate risks at once (e.g., Ciscar et al. 2011; Robinson et al. 2012; Eboli et al. 2010).

However, the application of economy-wide models to adaptation is still relatively rare, and important knowledge gaps remain. There is not even clarity about the direction of higher-order effects, although there is some evidence that they may exacerbate the initial effect (e.g., Bosello et al. 2007; Berrittella et al. 2006; Hallegatte 2008). The only area where indirect effects are routinely studied is agriculture, where there are detailed models of climate-induced changes in agricultural trade (e.g. Nelson et al. 2010; Reilly et al. 1994, 2007)

A practical problem with system-wide models is that their usual structure is not necessarily suited for climate change analysis. Land lost to coastal inundation, the effect of droughts and floods, and changes in water supply are difficult to project onto standard input-output tables or the social accounting matrix without additional assumptions, for example on productivity. Similarly, general equilibrium models measure long-term impacts, once the economy has had time to adjust. They offer a static comparison of two equilibria. The immediate repercussions and short-term costs of a shock are not captured (Fisher-Vanden et al. 2013).

Despite these difficulties, the system-wide effects of climate change deserve more attention. Economic systems are increasingly interconnected, and there is a suspicion that for some sectors indirect risks, and therefore the adaptation needs, dominate the direct effects of climate change.

There is some evidence of this for the UK, where the wider climate risks embedded in the typical consumption basket have been studied by ASC (2014).

Although system-wide analysis is still rare, its insights will feature in particular in sections 3.1 on private adaptation and 4.2 on adaptation costs.

2.4 Decision making tools

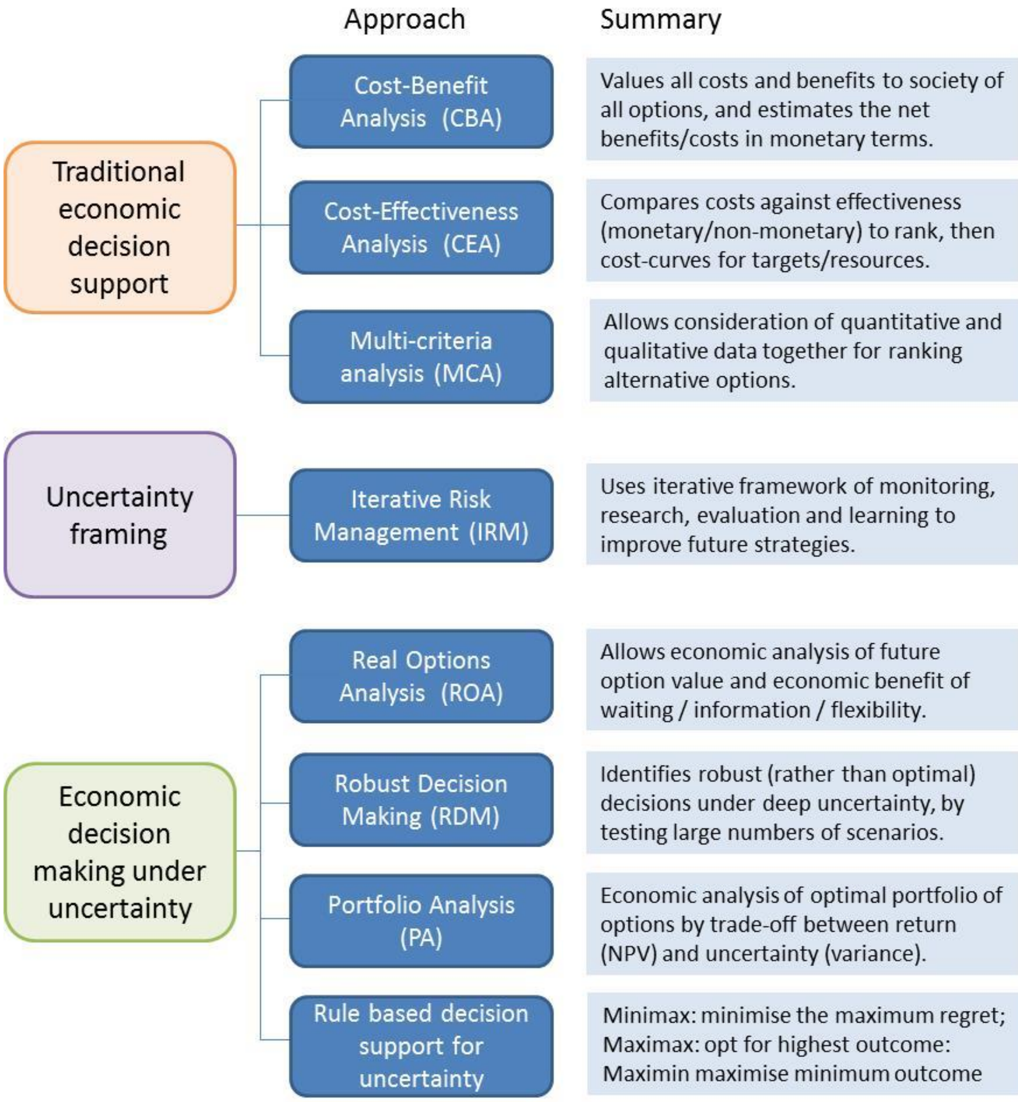
Climatic conditions have always been factored into economic decisions, for example in the crop choices of farmers or the design of coastal infrastructure. However, climate change presents new challenges to decision makers. It is not just that past climate statistics and hazard maps are no longer reliable. They are subject to continuous change in ways that are largely unknown. Tools to deal with this uncertainty are therefore a critical aspect of adaptation economics.

Many climate change economists believe that our understanding of climate change is not sufficient to satisfy the axioms of expected utility theory (see Heal and Millner 2014 for an accessible overview). What is more, although many climate uncertainties are epistemic (i.e. reducible) there is little prospect that they will be resolved over a meaningful timeframe. This has led researchers to explore models of what is variously called ambiguity, ignorance or deep uncertainty. That is, they are interested in decision making contexts where it is not possible to describe the full state space or assign credible probabilities to different states of the world.

Most of this work is motivated by the question of optimal emission reductions, but it applies equally, if not more so, to adaptation. As Heal and Millner (2014) point out, the level of uncertainty about possible climate outcomes is much higher in the case of adaptation than in the case of mitigation. Scientific uncertainty escalates the more interest shifts to the regional and local level. There is also much less information about secondary climate variables like precipitation, wind speeds, seasonal variations and weather extremes than there is about global mean temperature. Yet this is the kind of information that adaptation decision makers need.

Various decision making heuristics and tools have been put forward to make adaptation decisions under (deep) uncertainty (Hallegatte et al. 2012; Ranger et al. 2010; Watkiss and Hunt 2016). Figure 1 provides an overview. In situations where uncertainty is less deep (for example with respect to sea level rise) a traditional benefit-cost assessment may be possible, perhaps using probabilities and expected values (see Li et al. 2014 for applications).

Figure 1: **Appraisal tools to deal with climate uncertainty**



Source: Watkiss and Hunt (2016).

If there is a prospect that uncertainties will be resolved, analysts may proceed iteratively or choose an option value approach. A powerful example of these methods is Ranger et al. (2013), who apply adaptation pathways to identify flood protection options for the Thames estuary under various scenarios.

If the information base is insufficient, as it often will be, a non-probabilistic assessment may be required. The approach that has gained most prominence in this respect is robust decision making (e.g. Kuhnreuther et al 2013; Lempert et al. 2006; Lempert and Schlesinger 2000). Robust decision making uses a maximin philosophy to identify, either qualitatively or quantitatively, adaptation solutions that work under a range of possible climate scenarios. Good examples are Lempert et al. (2013), Bhave et al (2016) and Dessai and Hulme (2007).

We will return to decision making issues in section 3.4 on adaptation priorities.

3. The microeconomics of adaptation

A substantial part of the relevant literature analyses adaptation to climate change through the lens of applied microeconomics. The underlying paradigm is of economic agents that maximise their profits or welfare in the light of climatic risks (see Mendelsohn 2012 for a formal representation). Households and firms are thought to respond to climate signals by adjusting their behaviour. It is a reasonable assumption. However, outside the agriculture sector there are surprisingly few studies that document private adaptation behaviour.

Instead, adaptation is often analysed normatively and from the point of view of public policy. There is a suspicion, supported by some evidence, that private adaptation is not perfect. There are adaptation gaps and market imperfections which call for government intervention. Researchers have begun to explore how good adaptation decisions should look, particularly when dealing with climate uncertainty (see section 2), and they have developed prescriptions about who should do what and when.

3.1 Private adaptation

Most economic activities are exposed, directly or indirectly, to climatic factors. We should therefore expect the incidence of private adaptation to be widespread and diverse. Indeed, there is a clear expectation that most adaptation to climate change will be undertaken by private agents – households and firms. This is sometimes called autonomous adaptation to distinguish it from interventions by the public sector. However, the term is a misnomer. No adaptation actions happen autonomously. They are always the result of deliberate, sometimes complex decisions taken by the actors involved.

The richest empirical evidence of private adaptation is available on agriculture. Kurukulasuriya et al. (2011), Seo et al (2010), Seo and Mendelsohn (2008) and Wang et al. (2010) find clear (and not unexpected) differences in agricultural practices, such as crop choices, under different climate conditions. In the short term, farmers also respond to weather fluctuations by adjusting the size of their farm or moving into non-farm activities (Eskander and Barbier 2016; Mueller and Quisumbing 2011; Banerjee 2007; Kazianga and Udry 2006). In more advanced contexts they may have access to weather insurance (Barnett and Mahul 2007). A counterfactual analysis for Ethiopia found that such adaptation strategies can be highly beneficial, although the right combination of measures also matters (Di Falco and Veronesi 2013). Changing crop varieties had a positive impact on net farm revenues only when coupled with water or soil conservation strategies. It had no significant impact when implemented on its own.

Households similarly adjust their consumption in response to climatic factors. This is perhaps best documented for energy services. Both energy demand and the demand for associated products like air conditioning units fluctuates over the season and across climate zones (e.g. Auffhammer and Mansur, 2014; Mansur et al. 2008; Auffhammer and Aroonruengsawat, 2011; Eskeland and Mideska 2010; Rapson 2014; Rosenthal et al. 1995). The social benefits of these adjustments in terms of mortality and wellbeing are substantial (Barreca et al 2013; Deschênes and Greenstone 2011). There is also evidence from tourism, where holiday makers change destinations or adjust the date of travel in response to climate variables (Maddison 2001; Hamilton et al. 2005; Berrittella et al. 2006).

There is evidence that people may respond to severe weather shocks or worsening climate conditions by moving away (Boustan et al. 2012; Feng et al. 2010, 2012; Smith et al 2006; Henderson et al 2014). Such weather-induced migration is often temporary and usually domestic, rather than international (Beine and Parsons 2013). Relocation can be a powerful adaptation tool, for example away from threatened coastlines, though it is usually seen as a last resort (Penning-Rowsell et al 2013). There is also an important distinction between planned, proactive migration and reactive relocation in an emergency. The latter is a sign of adaptation failure.

There is surprisingly little analysis of adaptation behaviour in the business sector, certainly in the peer-reviewed literature (Linnenluecke et al. 2013). A good summary of the available evidence is an OECD survey by Agrawala et al. (2011b). The authors find that most firms manage current climate risks and many are aware of future climate change. However, few firms consciously engage in adaptation to climate change. Instead, climate risks are addressed under rubrics such as business continuity planning and supply chain management (see also Biagini and Miller 2013).

Businesses view climate change both as a risk and an opportunity (ASC 2014). A climate-resilient supply chain is a comparative advantage, and the need to adapt will create new demand for urban drainage solutions, water efficient appliances, risk management services and much else. Forward-looking entrepreneurs will pursue these opportunities, though the adaptation literature has been slow to document it. For example, there is evidence of considerable innovation in risk mitigation and water saving technology (Miao and Popp 2014, Conway et al. 2015).

3.2 Barriers to adaptation

While there is evidence of widespread, beneficial adaptation, there are also signs that people's response to climate risks is not always effective. There are many instances of insufficient adaptation or even maladaptation. The literature is also concerned with potential limits to adaptation, given that future climate risks may be much more severe than the effects of current climate variability (Adger et al 2009; Dow 2013).

There is particular concern about the ability of low-income countries and low-income population groups to adapt effectively. Low-income households are used to dealing with climate stress. However, their response strategies are often fragile (Dercon 2002) and probably insufficient in the face of anthropogenic climate change, which is a shock of a different nature and magnitude. There is what Burton (2009) called an "adaptation deficit": Low-income countries often lack the institutional, financial or technological capacity for effective adaptation.

Considerable research has gone into understanding the adaptation deficit. Gaps in "adaptive capacity", that is, in the ability to respond to climate risks, have been linked to factors such as literacy, income, income distribution, institutional quality, health spending and access to finance (Fankhauser and McDermott 2014; McDermott et al. 2013; Noy 2009; Kahn 2005). However, a complete list of all relevant aspects of adaptive capacity and how they interact is still lacking. Most measures of adaptive capacity (e.g. Brooks et al., 2005, Barr et al., 2010) simply add up the various contributing factors. In contrast Tol and Yohe (2002) and Yohe and Tol (2007) suggest that adaptive capacity may at least in part be determined by the “weakest link”, that is, by the factor that is least developed.

Differences in adaptation performance have also been documented across sectors and between economic agents. Carleton and Hsiang (2016) distinguish between responsive sectors, where damages fall as societies adapt (e.g. tropical cyclones, Hsiang and Narita 2012), and unresponsive sectors, where the relationship between temperature and impact is largely constant (e.g. economic productivity, Burke et al 2015). Di Falco et al (2011) find that adaptation levels among Ethiopian farmers vary depending on household size, as well as factors such as the availability of extension services and access to credit.

Researchers have compiled a long list of policy, market and behavioural failures that help explain shortcomings in adaptation performance (Biesbroek et al. 2011, Repetto 2008; Moser and Ekstrom 2010; Cimato and Mullan 2010). Complex, probabilistic adaptation decisions are known to be affected by cognitive barriers (e.g., Grothmann and Patt 2005). Other potential behavioural problems include inertia, procrastination and high discount rates. Within large organizations there are issues of perception, capabilities and resources, with adaptation often lacking the salience to attract senior management attention (Berkhout 2012). Stock markets fail to process climate information and factor climate risks into their valuations (Hong et al 2016).

Sobel and Leeson (2006) document how coordination problems, layered bureaucracy, defensive decision making and short-sightedness affected the response to hurricane Katrina. A review of the UK’s response to the 2007 winter floods found similar institutional barriers, including unclear and ill-defined responsibilities, a lack of joined-up strategies and the difficulty of dealing with multiple threats at the same time (Pitt 2008). Coordination problems across and between jurisdictions are also common in water management.

Market and policy failures affecting adaptation include insecurity over land titles, which can dis-incentivise investment in adaptation. In the property market, there may be asymmetric information between buyers and sellers about the risk profile of dwellings. There may be issues of moral hazard related to insurance cover or with at-risk communities holding out for government assistance. Path dependence may affect the choice between protection and relocation, with highly vulnerable locations defended because of their economic or historical significance.

The literature also highlights regulatory issues such as low water prices and inadequate abstraction rules (Agrawala 2005, Agrawala and Fankhauser 2008).

3.3 Adaptation and public policy

The presence of these barriers implies an important role for public policy to overcome market failures, correct policy distortions and incentivise private adaptation. Fankhauser and Soare (2013) recall the basic principles of public sector economics on the role of government to suggest three main roles for public policy.

The first role for government is to provide a policy environment that is conducive to effective private adaptation by incentivising the right actions and removing potential distortions. While this is uncontroversial, relatively little has been written on specific adaptation policies that would achieve this aim (Chambwera et al 2014). There is work on adaptation planning (e.g. Mullan et al. 2013) and capacity building (e.g., Biagini and Miller 2013), but there is no generally agreed adaptation policy tool kit, in the same way as there is consensus on the key planks of low-carbon policy. Instead, adaptation policies are considered in their sector contexts, as refinements to existing policy interventions. Adaptation is "mainstreamed" into the discussion on, for example, integrated water resource management, coastal zone planning, water pricing, weather insurance and payment for ecosystem services (see e.g., Agrawala and Fankhauser 2008).

The second role for government concerns the provision of climate-resilient public goods. This covers both the need to "climate-proof" conventional public goods like transport networks (Dietz et al. 2016) and public goods specifically dedicated to adaptation, such as flood defences (Ranger et al. 2013) and climate information services like early warning systems (Collier et al. 2008).

The public adaptation good that is best understood is coastal protection against sea level rise. Coastal protection studies have the advantage that sea level rise is one of the more predictable impacts of climate change. The costs and benefits of protection are also relatively easy to quantify, at least if the analysis is limited to hard measures like sea walls. The first studies trading off the cost of sea defences against the value of protected assets go back to the mid-1990s (Fankhauser 1995; Yohe et al. 1995), and they have been replicated, expanded and refined many times (e.g. Vafeidis et al. 2008; Bosello et al. 2007). A key challenge, as with all long-lived adaptation investments is accounting for uncertainty about future climate scenarios, an issue explored for example by Ranger et al (2013). See also section 2.4.

The third role of public policy is assistance for vulnerable groups that cannot adapt sufficiently themselves. The presence of an adaptation gap in poor countries and among poorer population groups suggests the need for capacity building, technical assistance and help with response plans (Watkiss 2016). Emergency services also play an important role in protecting the most vulnerable (ASC 2014). Castells-Quintana et al. (2016) discuss the role of social safety nets in aiding post-disaster recovery and redistributing income towards the poorest and most vulnerable (see also Dercon 2002). Aid agencies provide such support either in the form of cash transfers, which can also help to stimulate local markets, or in kind, in the form of e.g. food and shelter. Transfers may either be unconditional or tied to particular behaviour, such as school attendance.

3.4 Adaptation priorities

Adaptation to climate change is a long-term, iterative process that will extend over many decades. This long time horizon contrasts with the normal time frames of development planning, which are rarely more than five to ten years. The question of immediate adaptation priorities, and how interventions should be sequenced, is therefore a salient issue.

An obvious way to answer the prioritisation question is by comparing the net present value (NPV) of an adaptation investment at different times (Fankhauser and McDermott 2016). Bringing the investment forward makes sense if the NPV of acting early is greater than the NPV of acting later. In a stylized setup with only two time periods (early and later, denoted by subscripts 0 and 1) and three NPV components (costs C, early benefits B_0 and later benefits B_1) the difference between the two NPVs can be written as:

$$\Delta NPV = NPV^E - NPV^L = (C^L\delta - C^E) + (B_0^E - 0) + \delta(B_1^E - B_1^L) \qquad (2)$$

where δ is the discount factor and the superscripts E and L denote the strategy to adapt either early or later. We know $B_0^L = 0$ because late adaptation cannot have early benefits by definition. The three components of this simple equation point to three generic reasons why adaptation might be brought forward.

The first reason to accelerate adaptation is that early action may be cheaper than action later on, even after factoring in discounting (that is, $(C^L\delta - C^E) > 0$). This case is associated with the risk of locking in climate vulnerabilities that are difficult to reverse. For many long-term decisions it will be cheaper to factor in climate change at the outset, rather than retrofitting adaptation measures later. Decisions falling into this category include those on long-lived infrastructure (e.g. the design of sea ports, rail links and power stations), spatial planning (e.g. the location of new housing developments) and building design (e.g. the need for sustainable urban drainage systems).

The second reason to prioritise adaption is if acting now secures substantial early benefits (that is, B_0^E is large). This category is associated with win-win solutions, which make sense both as an adaptation measure and for broader economic or environmental reasons. Examples include ecosystem-based adaptation like mangrove protection (Das and Vincent 2009; Barbier 2007; Tri et al. 1998) and measures dealing with current climate variability and extreme weather events (e.g. Paul 2009; di Falco et al 2011).

The third reason to prioritise adaptation is if the long-term benefit of adaptation would be materially affected by a delay (that is, $(B_1^E - B_1^L)$ is large). This category is associated with adaptation measures that are slow to ramp up and need time to come to fruition. Examples include research and development into climate-resilient products and processes (Miao and Popp 2014, Conway et al 2015). Capacity building arguably also falls into this category, although it also will also have immediate benefits.

All three of these motivations are now recognised in adaptation policy and concrete interventions have been studied for each of them (Smith and Lenhart 1996; Ranger et al. 2014; Watkiss 2016; Watkiss and Hunt 2016). They are corroborated by results from integrated assessment models, which recommend building up a stock of adaptation capital early on (Agrawala et al. 2011a; Millner and Dietz 2015).

In a survey of current experience, particularly with adaptation in developing countries, Watkiss (2016) finds attractive benefit-cost ratios for measures as diverse as enhanced meteorological services, the better maintenance of drainage systems, integrated water resource management and sustainable agricultural land management (e.g., soil and water conservation, reduced tillage and the use of cover crops). Flood risk management measures can have benefit-cost ratios of 5:1 or more. The survey also highlights the value of ecosystem-based adaptation measures like shoreline restorations. In a general equilibrium analysis for Ethiopia, Robinson et al. (2012) demonstrate the power of economy-wide adaptation.

The assessment of adaptation priorities is complicated by deep uncertainty about future climate outcomes. Deep uncertainty is a defining feature of adaptation to climate change, and we have reviewed the decision making tools available to deal with it in section 2.4. These decision making rules are beginning to be applied to investments that risk locking in climate vulnerability (e.g. Ranger et al. 2013; Lempert et al. 2013; Dessai and Hulme 2007). In addition to using the right assessment tools, project developers are also responding to uncertainty by changing the design of their intervention, for example by opting for more flexible and reversible designs or by building in safety margins (Hallegatte 2009).

4. The macroeconomics of adaptation

While much adaptation economics is about individual decision making, there are also macroeconomic issues. The term "macroeconomic" is used loosely. There is little analysis on the link between adaptation and traditional macroeconomic concerns like price stability and growth. However, many adaptation questions are best analysed at an aggregate, economy-wide level. People's vulnerability and exposure to climate risks depends, among other factors, on economy-wide choices about economic diversification, spatial planning, urban design and infrastructure. Adaptation is entwined with these broader economic decisions and may have implications for macroeconomic aggregates like output and investment.

4.1 Adaptation and development

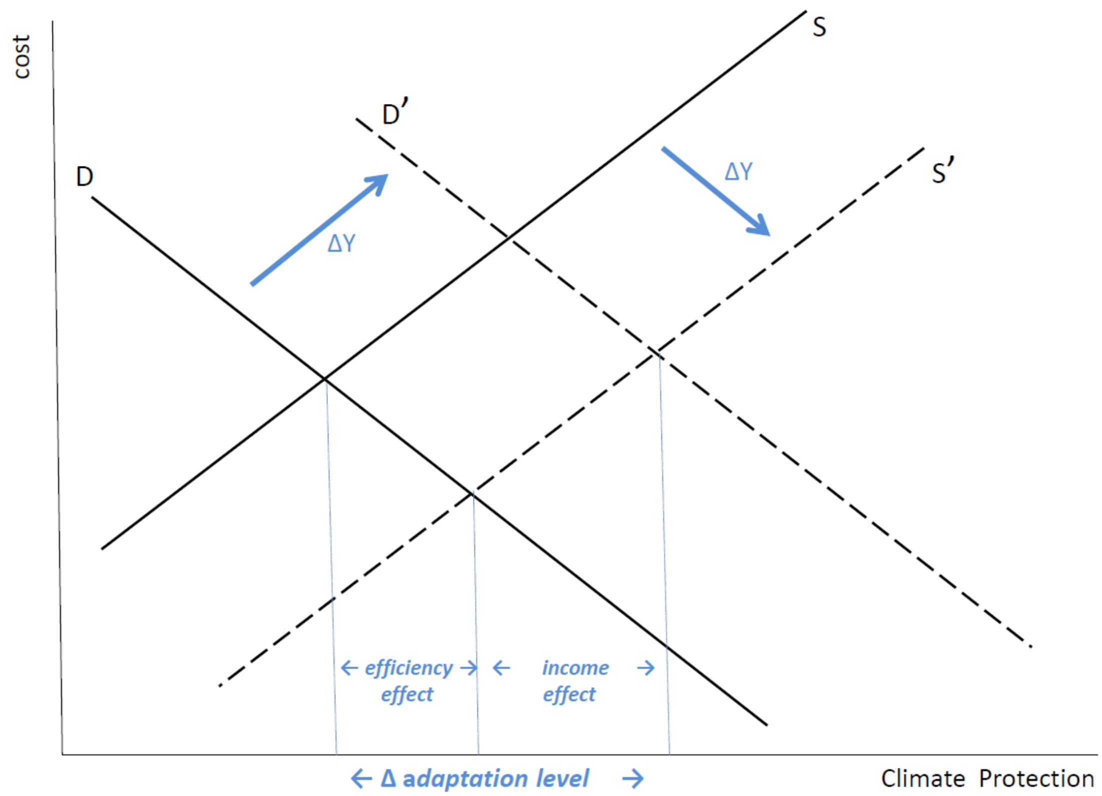
Development economists are acutely aware of the importance of climate change for development (Collier et al. 2008, World Bank 2016). They are concerned that unmitigated climate change will hit poor people particularly hard and may put development achievements at risk. But the climate risks poor countries face is also determined, to a considerable extent, by the development decisions they take. The challenge for development planners therefore is to make future economic development more climate-resilient. Millner and Dietz (2015) model this as the simultaneous accumulation of productive capital and adaptation capital.

The practical question that follows is how climate-resilient development differs from conventional development. In some of the first papers on the economics of climate change, Schelling (1992, 1997) claimed that economic development was the best form of adaptation, implying that conventional and climate-resilient development are one and the same. A similar conclusion might be drawn from Dell et al. (2012), who noted that climate (or more accurately, weather) extremes have a negative impact on growth in developing countries, but found no such effect in developed countries. Development, it appears, immunizes against climate risk.

Yet, there are differences between traditional and climate-resilient development and they are important (Fankhauser and McDermott 2016). To work them out it is useful to recall the basic determinants to climate risk. According to the IPCC, the risks associated with a given climate hazard are a function of the *vulnerability* and *exposure* of an economy to that hazard (Field et al 2012). Vulnerability and exposure can be reduced through appropriate *adaptation*. Of these three factors, economic development will generally lead to higher levels of adaptation. But vulnerability and exposure may either increase or decrease, depending of the development choices that are made.

The link between economic development and the level of adaptation has been studied by Fankhauser and McDermott (2014). They show that development progress affects both the supply and the demand for adaptation. On the supply side, the ability of economic agents to deal with climate risks is a function of technical capacity (e.g., information, skills), institutional factors (e.g., governance, quality of public services) and financial aspects (e.g., income, assets, access to credit), as we have seen in section 3.2. Many of these factors, like skills, good institutions and access to credit are strongly associated with development progress. As a consequence, the efficiency of producing the good "adaptation" (or climate protection) is likely to increase with higher levels of development. The supply curve, *S*, shifts to the right (Figure 2). On the demand-side there is a powerful income effect. Adaptation has a positive income elasticity, and as income per capita rises, the demand for climate protection, *D*, goes up. The combination of the two effects produces a significant increase in the provision of adaptation as societies developed (Figure 2).

Figure 2: **The supply and demand for adaptation as a function of income and efficiency effects**



Source: Fankhauser and McDermott (2014).

The effect of economic development on vulnerability and exposure is less clear-cut. As countries develop, they typically move away from agriculture into industry and eventually services. Sectors become more productive through the accumulation of physical and human capital. The location of economic activity may shift from rural areas to urban centres.

The net effect of most of these trends is ambiguous (Collier et al. 2008). Although agriculture is highly vulnerable to climate risks, a structural shift into industry and urban living improves resilience only if those sectors and locations are subject to lower risks than agriculture, which they may or may not be (Fankhauser and McDermott 2016). Much urban development has occurred along highly vulnerable coastlines (Hanson et al. 2011). Migrants to urban areas often end up in neighbourhoods that are subject to flooding and other environmental risks.

The type of development clearly matters therefore. Adaptation practitioners are responding to this observation by trying to incorporate climate risks more explicitly and proactively into development plans (e.g., World Bank 2016; Ranger et al 2014). They argue that the most effective way of improving climate resilience is by influencing the choices development planners make on issues like agricultural diversification, urban design, infrastructure investment and coastal development (Agrawala 2005; Fankhauser and McDermott 2016). Indeed, the time when these decisions are taken is a natural "entry point" to introduce adaptation into development planning (Dietz et al. 2016).

4.2 Adaptation finance and the cost of adaptation

The discussion on climate-resilient development is closely linked to the debate on climate finance. Developed countries have promised to support the adaptation and mitigation efforts of developing countries under the UN Framework Convention on Climate Change. Policy makers are therefore interested not just in effective adaptation strategies but also in the best way to finance those strategies. This policy interest is in turn generating analytical interest.

Adaptation economists have explored the aggregate costs of adaptation (Narain et al. 2011; World Bank 2010; UNFCCC 2007) and how to delineate them from baseline development spending (Callaway et al. 2006; Fankhauser and Schmidt-Traub 2011; McGray et al 2007). They have studied the economics of raising adaptation finance (Bowen 2011; Smith et al. 2011; Buob and Stephan 2013), the governance of those funds (Füssel et al 2012) and the allocation of capital to competing needs (Barr et al. 2010).

When climate negotiators started debating financial support for adaptation, they naturally wanted to know the likely overall costs of adaptation. It was not a question economists found easy to answer. Indicative estimates began to appear from around 2006 (UNFCCC 2007; Narain et al. 2011; World Bank 2010), but most of them were simple back-of-the envelope calculations. Even the more sophisticated estimates had substantial methodological shortcomings (Parry et al. 2009; Fankhauser 2010). They left important gaps in their coverage, considered only a small number of climate scenarios and there was no sense that the assumed level of adaptation was in any way optimal. For all these reasons aggregate cost numbers appear to be suspect. They are inconsistent with the results of more detailed studies at the sector level, and there is a sense that the latter approach is more promising.

Adaptation finance is meant to be provided over and above traditional development assistance. This additionality creates its own analytical complications (Klein 2010). Conceptually it is possible to design a development project under two different scenarios – with and without climate change – and treat the difference in costs as the incremental cost of adaptation (Agrawala and Fankhauser 2008). Callaway et al. (2006) have piloted this approach for the Berg river basin in the Western Cape. However, the analytical effort to do this is substantial and given the close links between adaptation and development (McGray et al 2007; Collier et al. 2008) the results are indicative at best. Moreover, the two forms of funding are fungible, which means recipient countries will realign their spending decisions to achieve the adaptation – development mix they desire (Eyckmans et al. 2015). These strategic interactions and the political economy of adaptation finance more broadly are still insufficiently understood.

4.3 Adaptation and mitigation

The exposition so far has treated adaptation as the response to an exogenously given (if unknown) change in climate. This is the reality in which adaptation decisions occur. Although most adaptation actors emit greenhouse gases, their carbon output is too small to have a tangible impact on the global climate. They are "climate takers".

Yet from an aggregate perspective, the relative role of adaptation and mitigation in the global response to climate change is an important question. Policy makers generally think of the two measures as complements, in the sense that the optimal policy response contains both adaptation and mitigation (Watkiss et al 2015). However, in strict economic terms adaptation and mitigation are more likely to be substitutes. That is, a reduction in the cost of one is likely to lower demand for the other (Buob and Stephan 2013; Ingham et al. 2005). If adaptation is cheap and effective there will be less need for mitigation. More adaptation reduces the marginal benefit of mitigation, and *vice versa*.

The models best suited to study the trade-off between adaptation costs, mitigation costs and residual damages are integrated assessment models (see section 2.1; for a theoretical exposition see Bréchet et al. 2013). Integrated assessment studies confirm that an effective policy response to climate change involves both adaptation and mitigation (Agrawala et al. 2011a; de Bruin et al. 2009; Bahn et al 2012). Either measure on its own would be insufficient to curtail the negative impacts of climate change. However, there is little agreement on the relative effectiveness, and therefore the right mix, of the two measures. The cost-effectiveness of adaptation in particular is difficult to calibrate at the aggregate, global level, and different modellers have made different assumptions (e.g., de Bruin and Dellink 2011).

There is more agreement on the ramp up of activities, with mitigation generally kicking in earlier than adaptation. Inertia in both the climate and economic system means mitigation benefits have longer lead-times (Bosello et al 2010). However, models that distinguish between proactive adaptation (sometimes called stock adaptation and modelled as a stock of adaptive capacity) and reactive adaptation (flow adaptation) observe a more even balance between adaptation and mitigation. As seen in section 3.4, economic agents are well advised to build up their adaptation stock early (Agrawala et al. 2011a; de Bruin 2011).

Integrated assessment models also offer insights on how the adaptation-mitigation choice depends on factors such as the discount rate (which affects mitigation more heavily) and climate uncertainty (which often favours reactive adaptation). These findings are important, but mostly of theoretical interest. International decision makers are not yet at a point where they need to fine-tune their mitigation and adaptation choices at the margin. After a flurry of activity around 2009-11 aggregate research on the mitigation-adaptation trade-off has levelled off, perhaps also influenced by broader criticism of integrated assessment models (Pindyck 2013; Stern 2013, 2016).

Nevertheless, the question remains significant. There continues to be interest in institutional and governance issues (Watkiss et al. 2015) and the adaptation-mitigation trade-off in particular sectors (e.g. Rosenzweig and Tubiello, 2007, on agriculture, and Kopytko and Perkins, 2011, on energy). These are important areas of future work.

5. Conclusions

Humans have always been good at adapting to diverse climatic conditions. Indeed, the ability to thrive in different climates is a defining characteristic of our species. Climate change will test that adaptability. Dealing with continuous, unknown and potentially violent climate change could be very different from the long-term adaptations to a settled climate, which humans have undertaken in the past. Yet the challenge is inescapable. A certain amount of climate change is now unavoidable and perhaps already observable. While emphasising the importance of cutting greenhouse gas emissions, the international response to climate change now puts equal emphasis on adaptation and mitigation.

While humans have a strong track record, adaptation does not happen automatically. Effective adaptation requires knowledge, planning, coordination and foresight. The decisions required can be intricate and multifaceted. This makes adaptation an interesting economic problem.

Adaptation economics has tackled the problem from several angles. There is a positive, empirical strand of analysis, which aims to understand the current adaptation behaviour of economic agents (often farmers) in response to climatic variations and extreme events. A second, more normative strand has asked what good adaptation should look like. Who should do what and when? A large part of that analysis is focused on public policy and the role of government in ensuring good adaptation outcomes. Finally, analysts with a more aggregate (macroeconomic) perspective have asked how adaptation relates to other economic decisions, such as development planning and greenhouse gas mitigation, and how it affects financial flows.

These enquiries have yielded important insights. We know that adaptation by private agents is widespread and manifold, and methodological advancements increasingly allow us to quantify it. We also know that adaptation is often hampered by behavioural barriers, market failures and policy distortions. There are adaptation gaps particularly, but not only, in developing countries. We are beginning to understand how good adaptation to climate change might look, in terms of the immediate priorities on which we should focus and how we should deal with climate uncertainty. And we are starting to understand how adaptation interacts with development decisions (for example on infrastructure) and wider economic trends (for example urbanisation). We know that we need to embed adaptation thinking into economic development plans.

But there is also a lot we do not yet know. There is a rich agenda for future research. We know a fair amount about the adaptation response of farmers, but much less about other sectors, such as the adaptation behaviour of firms. We do not know enough about measuring and assessing "adaptive capacity" and about practical barriers to adaptation. We have paid insufficient attention to the political economy of adaptation, for example the role of vested interests (e.g., homeowners in exposed areas) and the way in which different adaptation actors interact (e.g., competition for water rights).

We do not know a great deal about the aggregate costs of adaptation, but that is perhaps a lesser problem. With luck, the debate about adaptation finance has moved on from how much money is needed to how the available funds should be deployed. To answer that latter question we need to learn more about the effectiveness of adaptation policies at the sector level, including the performance of adaptation measures under different climate scenarios, their economy-wide effects and potential linkages to the mitigation agenda. There is a need for more, and more detailed, policy evaluation.

One of the most important challenges, and one of the more difficult, is to gain a better understanding of adaptation to more extreme forms of climate change, such as those associated with 3-4ºC of mean surface warming. Many researchers have highlighted potential limits to adaptation at that level of climate change. However, empirical evidence is hard to come by. Empirical analysis is, by design, restricted to the relatively modest levels of climate variation observed in the recent past. Nevertheless, it is clear is that those higher levels of warming could be extremely disruptive and adaptation strategies would have to change, perhaps fundamentally so. We need more research to understand those new adaptation strategies and how to switch from one adaptation regime to another. As long as 3-4ºC remains a possibility it seems an important line of enquiry.

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