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Adaptation to Climate Change

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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 behavior. However, adaptation is not autonomous as sometimes claimed. It requires knowledge, planning, coordination, and foresight. There are important knowledge gaps, behavioral barriers, and market failures that hold back effective adaptation and require policy intervention. We identify the most urgent adaptation priorities, including 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 interlinkages between adaptation and economic development, pointing out that decisions on industrial strategy, urban planning, and infrastructure investment all have a 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.

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), and its consequences will be addressed 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 (e.g., Watson et al. 1995). However, the attention of policy makers and (to a lesser extent) the economics profession has always been more focused on mitigation. This review synthesizes the state of knowledge on the economics of adaptation to climate change.

The nomenclature around adaptation can be confusing and is worth clarifying up front. Literature in related disciplines, particularly the risk management field, often uses 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 emphasize 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 to moderate the negative impacts 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-fertilization between economic studies of adaptation and the much larger literature on the economic impacts of climate change (surveyed by Carleton & Hsiang 2016, Dell et al. 2014). This review 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 recognized 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 those by Kahn (2016), Markandya et al. (2014), and Massetti & Mendelsohn (2015). In particular, Kahn and Massetti & Mendelsohn emphasize 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 review explores the decisions that both public and private economic agents 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 behavior.

The structure of the review is as follows. Section 2 discusses the main analytical tools that 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 offers 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, as well as adaptation finance and costs and the interplay between adaptation and mitigation. Section 5 concludes by summarizing our state of knowledge and outlining fruitful avenues for future research.

2. THE ANALYTICAL TOOLS OF ADAPTATION ECONOMICS

There are many analytical angles to studying adaptation. There is both theoretical and empirical analysis; some questions are positive, and many more are normative. There are microeconomic questions and macroeconomic issues. Within this diversity of analytical angles, some economic methods have proven to be more useful than others. Important insights have been gained from four main tools in particular: integrated assessment models, empirical (econometric) analysis, economy-wide simulation models, and decision-making 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 socioeconomic 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:

$$D(T) = argmin_{\mathrm{A}}[AC(A, T) + RD(A, T)], \tag{1}$$

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

In reality, Equation 1 was not explicitly modeled, 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 (e.g., changes in agricultural yields). However, the optimality assumption allowed modelers 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 Dynamic Integrated Climate–Economy (DICE) model, are still based on this structure (see Nordhaus & Sztorc 2013). However, there have also been attempts to separate out adaptation and create adaptation-integrated assessment models, which jointly optimize 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 (Regional Integrated Climate–Economy) (de Bruin

2011, de Bruin & Dellink 2011, de Bruin et al. 2009) and World Induced Technical Change Hybrid (WITCH) (Bosello et al. 2010). Agrawala et al. (2011a) use both of these platforms.

The simplifications needed to make integrated assessment models tractable and the difficulties in calibrating credible damage functions have been severely criticized, 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). Their structural shortcomings imply that the models should only be used to study key relationships, trends, and sensitivities and not used 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 & Surminski 2013 on the demand for insurance). However, researchers increasingly use large household-, firm-, or farm-level data sets 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 articles are concerned primarily with impact assessment and the effect of climatic factors on economic variables, such as labor productivity, output, and growth, rather than the benefits, costs, or extent of adaptation. However, many of the insights of all of these authors also apply to adaptation econometrics.

Researchers have sought to identify climate effects both cross-sectionally, by comparing impacts and/or adaptation behavior across different climate regimes, and intertemporally, 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., Kurukulasuriya et al. 2011, Mendelsohn et al. 1994, Seo & Mendelsohn 2008, Wang et al. 2010). Given the wide diversity of climates around the globe, these studies offer ample evidence of adaptation behavior. 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 et al. 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 such as 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 such as institutions are kept constant. Identification is therefore much easier. Its 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 shortcomings. 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 (Deschênes & Greenstone 2011, Hsiang & Narita 2012). Studying weather trends over longer periods (e.g., decadal weather averages rather than short-term shocks) can similarly help to identify long-term adaptation effects (Burke & Emerick 2016). We 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 global issue that affects all countries and most sectors. Therefore, it is important 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 (e.g., 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 labor supply and/or taking advantage of lower land prices until the economy is again in equilibrium (Banerjee 2007).

Although economy-wide effects are captured implicitly in econometric studies (see Section 2.2), analyzing 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 simultaneous climate risks (e.g., Ciscar et al. 2011, Eboli et al. 2010, Robinson et al. 2012).

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., Berrittella et al. 2006, Bosello et al. 2007, Hallegatte 2008). The only area where indirect effects are routinely studied is agriculture, in which 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 effects 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 indirect risks, and therefore the adaptation needs, dominate the direct effects of climate change for some sectors. There is some evidence of this for the United Kingdom, where the wider climate risks embedded in the typical consumption basket have been studied by the Adaptation Subcommittee of the Committee on Climate Change (ASC 2014). Although system-wide analysis is still rare, its insights feature in particular in Section 3.1 on private adaptation and Section 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, but they are subject to continuous change in ways that are largely unknown. Tools to address 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 & Millner 2014 for an accessible overview). Moreover, although many climate uncertainties are epistemic (i.e., reducible), there is little prospect that they will be resolved over a meaningful time frame. 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 & 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 as interest shifts to the regional and local levels. There is also much less information about secondary climate variables, such as 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 proposed to make adaptation decisions under (deep) uncertainty (Hallegatte et al. 2012, Ranger et al. 2010, Watkiss & Hunt 2016). **Figure 1** provides an overview of these methods. In situations where uncertainty is less deep (e.g., with respect to sea level rise), a traditional cost-benefit analysis may be possible, perhaps using probabilities and expected values (see Li et al. 2014 for applications).

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 presented by Ranger et al. (2013), who apply adaptation pathways to identify flood protection options for the Thames River estuary under various scenarios.

If the information base is insufficient, as it often will be, a nonprobabilistic assessment may be required. The approach that has gained most prominence in this respect is robust decision-making (e.g., Kunreuther et al. 2013, Lempert & Schlesinger 2000, Lempert et al. 2006). 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 found in Bhave et al. (2016), Dessai & Hulme (2007), and Lempert et al. (2013). We return to decision-making issues in Section 3.4 on adaptation priorities.

3. THE MICROECONOMICS OF ADAPTATION

A substantial part of the relevant literature analyzes adaptation to climate change through the lens of applied microeconomics. The underlying paradigm is of economic agents that maximize 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 behavior, which is a reasonable assumption. However, outside the agriculture sector, there are surprisingly few studies that document private adaptation behavior.

Instead, adaptation is often analyzed normatively and from the viewpoint of public policy. There is a suspicion, supported by some evidence, that private adaptation is not perfect. There are adaptation gaps and market imperfections that 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.

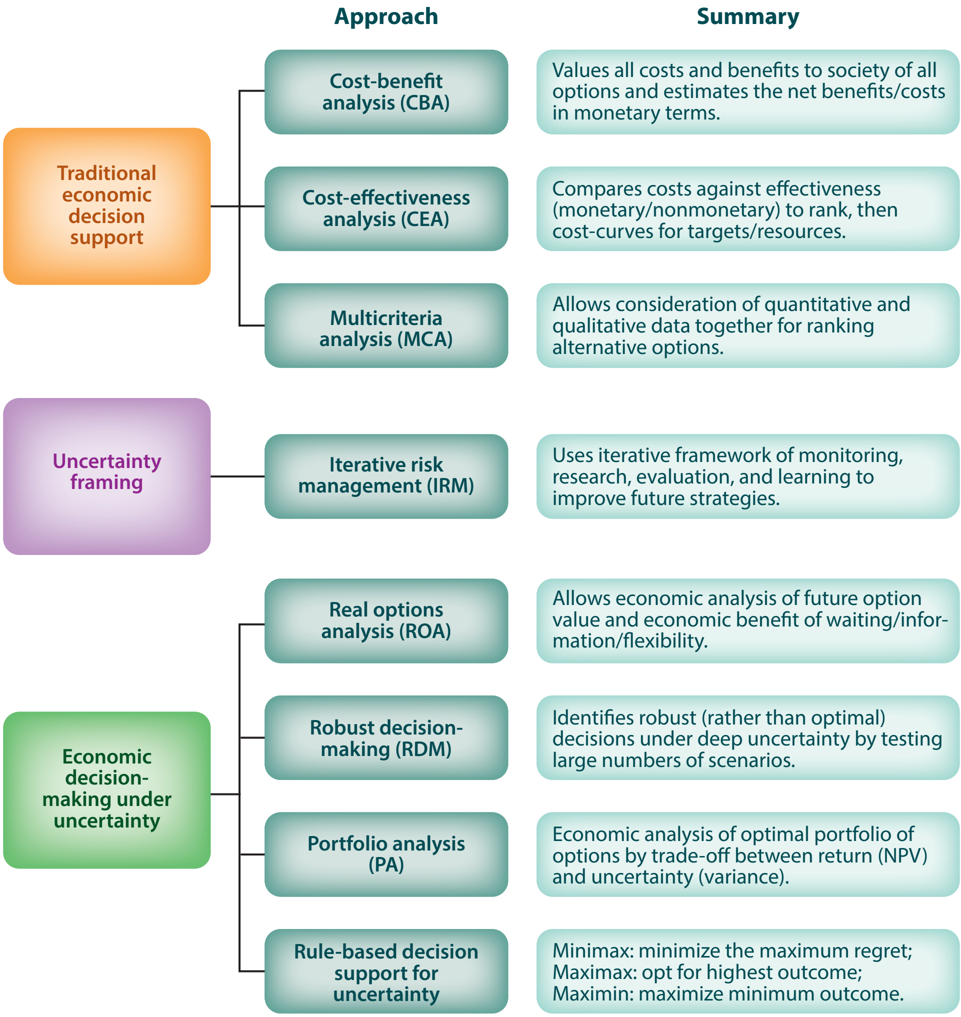

Figure 1

Appraisal tools to address climate uncertainty. The literature has proposed several tools and techniques that can support the appraisal of adaptation options. The choice of tool depends on the level of uncertainty. Figure adapted with permission from Watkiss & Hunt (2016). Abbreviation: NPV, net present value.

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, as 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 on agriculture. Kurukulasuriya et al. (2011), Seo et al. (2010), Seo & 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 nonfarm activities (Banerjee 2007, Eskander & Barbier 2016, Kazianga & Udry 2006, Mueller & Quisumbing 2011). In more advanced contexts, they may have access to weather insurance (Barnett & Mahul 2007). A counterfactual analysis of Ethiopia found that such adaptation strategies can be highly beneficial, although the right combination of measures also matters (Di Falco & 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 such as air conditioning units fluctuates over the season and across climate zones (e.g., Auffhammer & Aroonruengsawat 2011, Auffhammer & Mansur 2014, Eskeland & Mideksa 2010, Mansur et al. 2008, Rapson 2014, Rosenthal et al. 1995). The social benefits of these adjustments in terms of mortality and well-being are substantial (Barreca et al. 2013, Deschênes & Greenstone 2011). There is also evidence from tourism, where holiday makers change destinations or adjust the date of travel in response to climate variables (Berrittella et al. 2006, Hamilton et al. 2005, Maddison 2001).

There is evidence that people may respond to severe weather shocks or worsening climate conditions by emigrating (Boustan et al. 2012; Feng et al. 2010, 2012; Henderson et al. 2014; Smith et al. 2006). Such weather-induced migration is often temporary and usually domestic, rather than international (Beine & Parsons 2015). 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 behavior in the business sector, especially in the peer-reviewed literature (Linnenluecke et al. 2013). A good summary of the available evidence is an Organisation for Economic Co-operation and Development (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 & 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 more. 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 (Conway et al. 2015, Miao & Popp 2014).

3.2. Barriers to Adaptation

Whereas 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 et al. 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, or 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 & McDermott 2014, Kahn 2005, McDermott et al. 2013, Noy 2009). 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., Barr et al. 2010, Brooks et al. 2005) simply add up the various contributing factors. In contrast, Tol & Yohe (2007) and Yohe & Tol (2002) suggest that adaptive capacity may at least in part be determined by the weakest link or the factor that is least developed.

Differences in adaptation performance have also been documented across sectors and between economic agents. Carleton & Hsiang (2016) distinguish between responsive sectors, where damages fall as societies adapt (e.g., tropical cyclones; Hsiang & 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 behavioral failures that help explain shortcomings in adaptation performance (Biesbroek et al. 2011, Cimato & Mullan 2010, Moser & Ekstrom 2010, Repetto 2008). Complex, probabilistic adaptation decisions are known to be affected by cognitive barriers (e.g., Grothmann & Patt 2005). Other potential behavioral 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 the attention of senior management (Berkhout 2012). Stock markets fail to process climate information and factor climate risks into their valuations (Hong et al. 2016).

Sobel & Leeson (2006) document how coordination problems, layered bureaucracy, defensive decision-making, and shortsightedness affected the response to Hurricane Katrina in the southern United States. A review of the United Kingdom'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 simultaneous threats (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 disincentivize 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 coverage 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 & 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 incentivize private adaptation. Fankhauser & 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 incentivizing the right actions and removing potential distortions. Although 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 & Miller 2013), but there is no generally agreed-upon adaptation policy tool kit similar to the 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 such areas as integrated water resource management, coastal zone planning, water pricing, weather insurance, and payment for ecosystem services (e.g., Agrawala & 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, such as transport networks (Dietz et al. 2016), public goods specifically dedicated to adaptation, such as flood defenses (Ranger et al. 2013), and climate information services, such as 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 such as sea walls. The first studies trading off the cost of sea defenses against the value of protected assets go back to 1995 (Fankhauser 1995, Yohe et al. 1995), and they have been replicated, expanded, and refined many times (e.g., Bosello et al. 2007, Vafeidis et al. 2008). As with all long-lived adaptation investments, a key challenge is accounting for the uncertainty about future climate scenarios, an issue explored by Ranger et al. (2013) (also see 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 postdisaster recovery and redistributing income toward 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 such items as food and shelter. Transfers may either be unconditional or tied to particular behavior, 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 are therefore salient issues.

An obvious way to answer the prioritization question is by comparing the net present value (*NPV*) of an adaptation investment at different times (Fankhauser & 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 *NPV*s can be written as:

$$\Delta NPV = NPV^{\mathrm{E}} - NPV^{\mathrm{L}} = \left(C^{\mathrm{L}}\delta - C^{\mathrm{E}}\right) + \left(B_0^{\mathrm{E}} - 0\right) + \delta\left(B_1^{\mathrm{E}} - B_1^{\mathrm{L}}\right), \tag{2}$$

where δ is the discount factor, and the superscript E and L denote the strategy to adapt either early or later. We know that $B_0^{\mathrm{L}} = 0$ 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, $(C^{\mathrm{L}}\delta - C^{\mathrm{E}}) > 0$. 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 prioritize adaptation is if acting now secures substantial early benefits (i.e., 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 adaptations such as mangrove protection (Barbier 2007, Das & Vincent 2009, Tri et al. 1998) and measures addressing current climate variability and extreme weather events (e.g., di Falco et al. 2011, Paul 2009).

The third reason to prioritize adaptation is if the long-term benefit of adaptation would be materially affected by a delay, that is, $(B_1^{\mathrm{E}} - B_1^{\mathrm{L}})$ 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 (Conway et al. 2015, Miao & Popp 2014). Capacity building arguably also falls into this category, although it will also have immediate benefits.

All three of these motivations are now recognized in adaptation policy, and concrete interventions have been studied for each of them (Ranger et al. 2014, Smith & Lenhart 1996, Watkiss 2016, Watkiss & 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 & 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, 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 such as 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 address it in Section 2.4. These decision-making rules are beginning to be applied to investments that risk locking in climate vulnerability (e.g., Dessai & Hulme 2007, Lempert et al. 2013, Ranger et al. 2013). 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

Whereas much of 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, such as price stability and growth. However, many adaptation questions are best analyzed at an aggregate, economy-wide level.

People's vulnerability and exposure to climate risks depend on economy-wide choices about economic diversification, spatial planning, urban design, and infrastructure, among other factors. Adaptation is entwined with these broader economic decisions and may have implications for macroeconomic aggregates, such as 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 that poor countries face are also determined to a considerable extent by the development decisions they take. Therefore, the challenge for development planners is to make future economic development more climate resilient. Millner & Dietz (2015) model this as the simultaneous accumulation of productive capital and adaptation capital.

The practical question that follows is, How does climate-resilient development differ from conventional development? In some of the first articles 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 they found no such effect in developed countries. Development apparently immunizes against climate risk.

Yet there are important differences between traditional and climate-resilient development (Fankhauser & McDermott 2016). To explain them, 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 & 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 handle 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 described in Section 3.2. Many of these factors, such as 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 develop (**Figure 2**).

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 centers.

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 & McDermott 2016). Much urban development has occurred

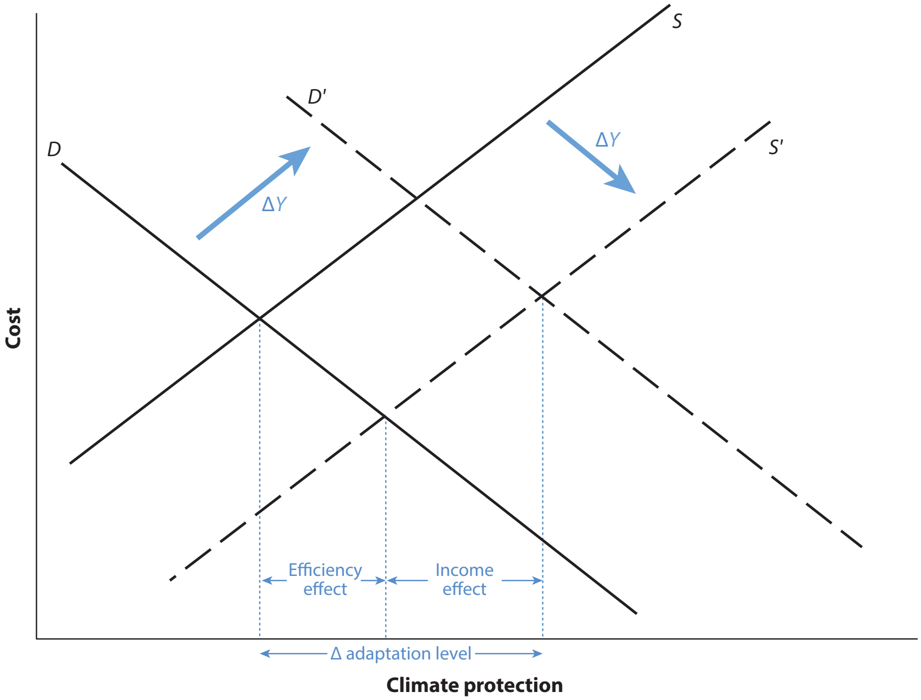

Figure 2

The supply and demand for adaptation as a function of income and efficiency effects. Development progress affects both the supply (*S*) and the demand (*D*) for adaptation. On the supply side, the efficiency of producing the good adaptation is likely to increase with higher levels of development. On the demand side, the demand for climate protection goes up as incomes rise. The combination of the two effects produces a significant increase in the provision of adaptation as societies develop. Figure adapted with permission from Fankhauser & McDermott (2014).

along highly vulnerable coastlines (Hanson et al. 2011). Migrants to urban areas often end up in neighborhoods that are subject to flooding and other environmental risks.

Therefore, the type of development clearly matters. Adaptation practitioners are responding to this observation by trying to incorporate climate risks more explicitly and proactively into development plans (e.g., Ranger et al. 2014, World Bank 2016). They argue that the most effective way of improving climate resilience is by influencing the choices development planners make on issues such as agricultural diversification, urban design, infrastructure investment, and coastal development (Agrawala 2005, Fankhauser & 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 United Nations 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 consequently generating analytical interest.

Adaptation economists have explored the aggregate costs of adaptation (Narain et al. 2011, UNFCCC 2007, World Bank 2010) and how to delineate them from baseline development spending (Callaway et al. 2006, Fankhauser & Schmidt-Traub 2011, McGray et al. 2007). They have studied the economics of raising adaptation finance (Bowen 2011, Buob & Stephan 2013, Smith et al. 2011), 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 that economists found easy to answer. Indicative estimates began to appear from approximately 2006 (Narain et al. 2011, UNFCCC 2007, World Bank 2010), but most of them were simple back-of-the-envelope calculations. Even the more sophisticated estimates had substantial methodological shortcomings (Fankhauser 2010, Parry et al. 2009). They left important gaps in their coverage and considered only a small number of climate scenarios; there was also no sense that the assumed level of adaptation was in any way optimal. For all of 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 & Fankhauser 2008). Callaway et al. (2006) have piloted this approach for the Berg River Basin in the Western Cape of South Africa. However, the analytical effort involved is substantial, and given the close links between adaptation and development (Collier et al. 2008, McGray et al. 2007), 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 therefore 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 consider 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 & 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, Bahn et al. 2012, de Bruin et al. 2009). 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 modelers have made different assumptions (e.g., de Bruin & 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 that mitigation benefits have longer lead times (Bosello et al. 2010). However, models that distinguish between proactive adaptation (sometimes called stock adaptation and modeled 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 (that affects mitigation more heavily) and climate uncertainty (that often favors 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 in 2009–2011, aggregate research on the mitigation–adaptation trade-off has leveled off, perhaps also influenced by broader criticism of integrated assessment models (Pindyck 2013; Stern 2013, 2016).

Nevertheless, the question remains significant (Klein et al 2007). 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., Kopytko & Perkins 2011 on energy; Rosenzweig & Tubiello 2007 on agriculture). These are important areas for 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 emphasizing the importance of cutting greenhouse gas emissions, the international response to climate change now puts equal emphasis on adaptation and mitigation.

Although humans have a strong track record of adaptation to past climate change, this 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 behavior of economic agents (often farmers) in response to climatic variations and extreme events. A second more normative strand has asked how good adaptation should look. 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 behavioral 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. Moreover, we are starting to understand how adaptation interacts with development decisions (e.g., on infrastructure) and wider economic trends (e.g., urbanization). We know that we need to embed adaptation thinking into economic development plans.

However, there is also a lot we do not yet know, which represents 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 behavior 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 how different adaptation actors interact (e.g., competition for water rights).

We know little 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 but difficult challenges is to gain a better understanding of adaptation to more extreme forms of climate change, such as those associated with 3–4°C 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 increases of 3–4°C remain a possibility, it seems an important line of inquiry.

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